UNDERGROUND COAL GASIFICATION:
EVALUATING ENVIRONMENTAL BARRIERS

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EXECUTIVE SUMMARY

Underground coal gasification (UCG) is a term applied to a number of different techniques that can produce a fuel or synthesis gas mixture from coal seams. Since experimental research on UCG started in the Soviet Union in the 1930s there has been a progressive change in the technologies used to access the coal from the early work involving mined tunnels to the more recent use of directionally drilled wells. There has also been an improvement in operating methods to increase the efficiency of operation and to reduce the environmental impact. The Soviet research effort on UCG was substantial and far exceeds that of any other country, but there have also been significant research programmes on UCG in the USA, UK, European Community and China.

A detailed analysis of the Greenhouse emissions and costs for electricity generation was performed considering two UCG cases, one using conservative estimates of performance at the selected site and the other an artificially degraded performance to provide an indication of the sensitivity of the analysis to UCG performance, and a case based on a current technology surface gasifier plant. Three variations of plant were considered based on an integrated gasification combined cycle (IGCC) process using a combined cycle gas and steam turbine system. These were a basic IGCC system (IGCC), an IGCC system where carbon dioxide was removed from the fuel gas (IGCC-CO$_2$) and an IGCC system where a shift reactor was used to convert carbon monoxide to carbon dioxide before carbon dioxide removal (IGCC-Shift). All nine of these cases were simulated and costed to examine Greenhouse emissions and electricity cost. In the basic IGCC configuration, the UCG systems are not particularly attractive and compare poorly with the air-blown UCG figures based on the Chinchilla trial. However, with the simple carbon dioxide removal system there are significant benefits in terms of Greenhouse gas reductions and electricity is produced at a cost comparable to conventional coal fired power plant. The carbon dioxide removal plant also reduces the sensitivity of the plant emissions and cost to the UCG operational performance. The combination of UCG in an IGCC plant with carbon dioxide removal for sequestration appears a cost effective method for reducing Greenhouse emissions. In all cases the use of a shift reactor before carbon dioxide removal results in a significant increase in electricity production cost that appears difficult to justify in a competitive electricity supply industry without some form of subsidy.

This study highlights some significant issues regarding the behaviour of existing gas turbine systems. The UCG-sourced fuel gas appears less suitable for existing gas turbine systems than surface gasifier fuel gas and is likely to have higher Greenhouse emissions in standard IGCC systems, despite having lower carbon content, due to poor performance in the gas turbine system. This exposes a problem with the current trends in clean coal technology using gas turbines with low carbon fuels and is an area of research for gas turbine specialists. If carbon dioxide removal is added to the process, the fuel gas changes dramatically for UCG sourced gas and the higher methane content gas performs well in the gas turbine system, resulting in substantial Greenhouse gas emission reductions. The use of a shift reactor to convert carbon monoxide to carbon dioxide prior to the removal process has a relatively minor impact on the UCG cases, because the methane is not removed, but causes a major reduction in the surface IGCC plant Greenhouse emissions due to the high carbon monoxide content of the raw fuel gas. However, this process option is problematic, as none of the currently available gas turbine systems are suitable to use the fuel gas resulting from this processing due to the high hydrogen content. This is a significant issue in the development of clean coal technologies in general.

A detailed evaluation of the geotechnical and hydrological impacts of UCG was performed on two scales, the local area of the site and the region. Key issues that were examined include the effects on groundwater supplies, subsidence and potential for groundwater contamination. On the base scenario it was predicted that the average water inflow could be up to 0.7m$^3$/tonne of coal gasified and the local water table drawdown at the site would be up to 17m during gasification. The extent of the drawdown exceeding 0.5m (barely detectable) was predicted to be at most 10km from the UCG site during gasification and 20km during cleanup (although this would be reduced to about 10km with a revised cleanup plan). The cleanup plan as modelled is excessive and constitutes an extreme worst case, as it pumps out water at 6 times the rate that it is removed in the gasification phase for the 2 years of the cleanup phase, however, water levels were still predicted to return to their pre-gasification levels within
approximately 2 years following cleanup. Put in context of other resource utilisation processes such as underground mining and coal seam methane extraction, the water use for UCG is appreciably less due to the pressurisation of the cavity during operation. The UCG process as defined would also be much smaller scale than typical utilisation projects of other types. Subsidence at the site was predicted to be a maximum of approximately 0.5m directly above the cavity, with small variations depending on the site design, which is unlikely to have a significant impact on post-operation land use given the current use as grazing land. Lower impact options for the UCG operation are available if the subsidence is a concern.

The potential for groundwater contamination is a more complex consideration, as it is strongly dependent on the quality of the cleanup process. Concentration of salts due to evaporation in the cavity is unlikely to have any significant impact, as these will be mostly extracted in cleanup or rapidly diluted to near background levels when the cavity refills. Contamination of the groundwater due to dispersal of soluble organics, such as benzene, from residual non-aqueous phase organics in the affected area is more complex to analyse. There is insufficient data to accurately model the decay in the release rates of these compounds and the rates of adsorption and reaction that may remove them from the water, so the modelling assumed they would continue to be released at a constant rate and flow. Therefore, the contaminants are predicted to slowly spread into the coal seam and overlying aquifers. The rate of spread is extremely slow, so additional cleanup operations could be performed a considerable time after the operations without widespread contamination, but it will require careful placement of monitoring wells to detect the spread early. The dilution of contaminants with flow is likely to mean that concentrations will not be significant unless a significant source of drinking quality groundwater is close to the coal seam. It is expected that a well monitoring system would be required for a number of years after operation of a significant UCG site.

The social issues that are likely to affect a prospective UCG project were examined in three workshops involving experts, city dwellers or country people. There were some differences in the benefits and concerns as viewed by the different groups, with more emphasis on local impacts from country people that are likely to be near a development. Environment, safety, economics and trust in the operators were noted as key areas of interest. Surprisingly, there was no direct mention of Greenhouse emissions and groundwater was not a primary concern of the members of the public involved. This contrasts to a UK study of public attitudes that suggested that UCG would only be acceptable in combination with carbon dioxide sequestration. A process such as UCG makes an interesting case study in this type of public dialogue, as there is very little knowledge of the process in the general public. Therefore, all information on the process would have to be supplied into the dialogue and the outcomes would be relatively independent of external influences.

Legislation that impacts on UCG operations is quite scarce and it would be expected that a commercial site would have environmental requirements set by negotiation with the regulatory authorities. This is a challenge when evaluating the environmental performance of the process and most of the predictions of performance in this study can not be definitely compared to set limits. For example, a key concern regards groundwater contamination, but there are no specific limits for the materials that are likely to be released. Therefore, most findings of this study can be regarded as qualitative and represent an expectation that the results will, or will not, be acceptable based on reasonable limits being set by regulators. This is an important issue and is difficult to resolve without having a genuine proposal for a UCG operation that can be discussed with government authorities. The Queensland government has stated that regulations will be published for UCG operations in the future, but has not commenced the public review of the proposed regulations yet.

As a general conclusion, the study has not found any critical issues that are likely to prevent implementation of UCG in Australia. However, there are some areas of design and operation of UCG processes and social engagement that require care. The impact of UCG in terms of groundwater use and subsidence appear acceptable, but the operating techniques used, especially cleanup, require careful planning and monitoring to minimise the risks of groundwater contamination. Some process options appear to offer cost effective reductions in Greenhouse emissions in comparison with other technologies.
and optimisation of these may prove beneficial. No significantly hindering social or legislative issues were found, but further engagement with the public and regulatory authorities is advised.
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Narendra Dave and Thong Do of CSIRO Energy Technology determined the performance and costs of the carbon dioxide removal plant and shift reactors for the different plant configurations in Section 5 and authored Appendix B. Narendra Dave was also of assistance in providing advice regarding the performance criteria that are of importance in process simulation of IGCC plants.

Robert Virtue of GHD Pty Ltd assisted in the modelling of regional hydrology and contaminant spread in Section 6.
RELATED CSIRO PUBLICATIONS

Energy Transformed Flagship Reports


Other Reports:
Beath AC (2003) Gasification of coal in-situ (United Kingdom and CSIRO Research sections), CSIRO Exploration and Mining Report 1168R.

Beath AC and Su S (2003) Gasification of coal in-situ (USA, China, Australia, New Zealand and Modelling sections), CSIRO Exploration and Mining Report 1110C.


Papers:


1 INTRODUCTION

1.1 Scope
Since 1999 CSIRO has been actively involved in research into underground coal gasification (UCG) technologies and the issues involved in the use of this type of technology in Australia. This report focuses on the aspects of UCG technologies that have the potential to impact on the environment and, therefore, the suitability of the technologies for use in Australia on a large scale. In some parts of the study it is important to consider the scale and purpose of the UCG plant, so it is assumed to be electricity generation on a significant scale (nominal net output 400MW_e) in a combined cycle gas turbine plant. The key areas of UCG that are considered include:

- Site selection
- Process design and operational behaviour
- Greenhouse gas emissions (incorporating economics)
- Groundwater and subsidence
- Social and legislative issues

1.2 Drivers for UCG
Currently there is renewed interest worldwide in UCG technology, with countries as diverse as the UK, India, China and Australia having active research programmes. The most obvious driver in most cases for this is energy security, with the UK expecting depletion of North Sea natural gas stocks and both China and India having shortages of natural gas and electricity. In Australia, although there are plentiful supplies of mined coal, analysis suggests that low cost fuel or synthesis gas could be generated from the large resources of coal that are not economically viable to mine. Additionally, advances in drilling, remote sensing and control technologies are likely to improve economic, operating and environmental performance of UCG processes. The production of low cost fuel gas may provide a lower cost route to implementation of clean coal technologies for electricity generation, compared to surface coal gasification, while low cost synthesis gas could lead to development of new chemical industries, in particular one producing synthetic liquid fuels using the rapidly improving Fischer-Tropsch technology.

In summary, there are currently a number of drivers in Australia that together warrant a detailed assessment of the viability of UCG, namely:

- Past UCG experience indicates that Australia has large resources of coal that appear suitable for use in producing high quality synthesis or fuel gas using demonstrated UCG techniques.
- Advances in drilling, remote sensing and control technologies are likely to increase the accuracy of site characterisation and improve the operating and environmental performance of UCG processes.
- UCG may provide a lower cost route to implementation of clean coal technologies for electricity generation.
- UCG has the potential to provide a cost effective synthesis gas to substitute for natural gas in processes such as Fischer-Tropsch technologies for the synthesis of liquid fuels.

1.3 Hindrances to UCG implementation
One of the key hindrances to large scale UCG implementation is that it has not been done outside countries of the former Soviet Union. This is perhaps the most significant threshold, as the implementation in the Soviet Union was not in a transparently competitive environment and there is distrust in Western countries of the Soviet documentation, especially regarding environmental issues. Regardless of this, if the drivers discussed above are strong enough, it would be expected that commercial interests would use published UCG technologies given that economic analyses indicates financial viability. The reason why this has not happened appear to be strongly based on the availability of cheap natural gas or mined coal in the regions with good coal deposits for UCG. There is little or no commercial advantage for UCG in these situations and the relatively novelty of the UCG technology is detrimental to investment. This hindrance will disappear where natural gas or mined coal are in short supply or expensive, which explains the renewed interest in UCG in the UK, China, India and Japan.
The other significant hindrance is a lack of knowledge of the environmental impacts of large scale UCG implementation, specifically concerns about the potential for groundwater contamination. The concerns largely arise from specific trials of UCG in the 1970s in the USA, where groundwater remediation was required due to organic contaminants from the UCG cavity migrating into the overlying aquifer. The requirement for remediation work was extensively published and, despite this being due to specific faults in the UCG trials in question that were remedied in subsequent trials in the USA, it is necessary to explicitly address the likelihood of this type of problem in developing a UCG proposal for commercial implementation. Other potential environmental issues are less well published, but the current procedures for gaining environmental licences require that a full analysis of environmental performance is conducted and gaps in the understanding of behaviour of a large UCG site constitute hindrances to development of the technology. Public perception of UCG technology, in particular with regard to environmental performance, will also be important and could constitute a hindrance to development if unfavourable.

Previous trials of UCG have also suffered from poor selection of the site and inadequate analysis of the site characteristics. This is probably a symptom of the trials being small scale experiments, so site characterisation was on a restricted budget. It is difficult to see this occurring for a full commercial development, but it should be noted that exploration for a UCG site should be performed to a similar degree of accuracy as for an underground mine. The coal seam has to be accurately modelled, overburden characteristics determined and hydrogeological analysis completed prior to design and construction of the UCG reactors.

In summary, significant hindrances to large commercial development of UCG in Australia are likely to be:

- A lack of competitive advantage in the presence of cheap natural gas and/or mined coal.
- Operating risk due to the relatively unproven performance of UCG on a large scale.
- Uncertainty regarding environmental performance.
- Public perception.
- Poor site selection and characterisation.

**1.4 Important concepts of UCG**

There has been considerable variation in the methods used for UCG since experimental work started in the 1930s. A discussion of the history, techniques, experimental trials and operational issues of underground coal gasification (UCG) can be found in Appendix A. Key issues are discussed below.

**1.4.1 Fundamentals**

Underground coal gasification involves the same basic reactions as other types of coal gasification, namely coal devolatilisation, combustion, steam gasification, carbon dioxide gasification and hydrogen gasification. A schematic representation of the processes is given in Figure 1.1, showing a progression from high temperatures around the oxidant injection point at the left to low temperatures at the production well to the right. After oxygen has been depleted by the combustion processes, the temperature of the gas decreases due to a combination of endothermic gasification reactions, evaporation of moisture and heat loss to the surrounding coal and rock. The temperature of the gas has an impact on the reactions that can occur at significant rates, as gasification reactions will only occur rapidly at moderate to high temperatures. At lower temperatures devolatilisation will still occur, but towards the production hole it is likely that only coal drying will occur. A process that is not shown, but can be significant, is the degassing of coal bed methane into the cavity and this may elevate the product gas methane content when gasifying gassy coal seams. At all stages the gas composition will change to approach the equilibrium composition, but at lower temperatures the rate of change of composition will be slow and the product gas may have ‘frozen’ at a composition resembling equilibrium at a higher temperature.

The product gas is, therefore, a mixture of the products from all of the reactions and includes methane, hydrogen, carbon monoxide, carbon dioxide and various higher hydrocarbons. The exact composition will depend on a number of factors including the quantity of heat lost to the surrounding rock, the amount of water that flows into the reacting area, the amount of coal that participates in the reactions, the
proportion of the coal that is left unreacted, the temperature at which the reactions occur and the residence time of the gas at different temperatures in the cavity. An approximate indication of the gas composition can be obtained for a specific site by performing a mass and energy balance combined with a gas equilibrium calculation; however assumptions have to be made regarding heat losses, water flows, quantity of coal affected and the proportion of residual char. These can be based on past experimental experience or the results of more accurate modelling studies using the site characteristics. The product gas is generally described as either fuel gas or synthesis gas (syngas), depending on the intended end use. Changes in the operating parameters, such as the oxygen feed rate and pressure, can be used to modify the product gas composition to improve calorific value as a fuel or to adjust the hydrogen to carbon monoxide ratio as a synthesis gas.

![Figure 1.1: Schematic of the processes involved in UCG](image)

1.4.2 Site characteristics
A large range of sites with different characteristics have been used in past UCG trials and it has been determined that the operational performance is strongly dependent on the site. A detailed description of the impacts of site characteristics on operations is given in Appendix A, but the key criteria for a successful UCG site can be summarised as:

- Thick coal seam with minimal discontinuities
- Structurally robust overburden with low permeability
- Hydraulically sealed coal seam
- Ash content less than 40% (approximately)
- No good quality groundwater near the coal seam

The depth of the coal seam may also be important to the functionality of the process utilising the UCG product gas, as the operating pressure of the gasifier is limited to the hydraulic head at the coal seam.

1.4.3 Techniques
A large number of gasification techniques have been used at UCG trials in the past with this, to some extent, denoting technology improvements with time. The general trend has been to reduce the use of mining in favour of use of drilled wells, with more recent techniques involving advanced directional drilling technology to reduce the total amount of drilling required. On face value, all of the techniques are simply a method of positioning injection and production wells in the coal; however there are distinct
differences in how gasification proceeds with some techniques. The techniques most likely to be applied in Australia are variants of the vertical wells technique used extensively in countries of the former Soviet Union and variants of the CRIP (controlled retracting injection point) technique involving parallel, directionally drilled wells (see Appendix A for more detail). The vertical wells approach is more appropriate for relatively shallow (<300m) coal seams, as the grid of regularly spaced wells requires excessive drilling at greater depth, while the directionally drilled CRIP-type systems are suited to deeper seams, where the higher cost of the wells can be justified due to the reduction in the number of wells required. In both approaches it is typically desired to delineate a block of coal and gasify it completely, leaving only small pillars of coal between blocks to isolate the different cavities during operation. An exception to this is with shallow coal seams, where relatively narrow (<16m) strips of coal may be selectively removed to reduce the impact of subsidence at the surface, however this approach results in lower resource recovery.

1.4.4 Operating methods
The methods used to start and operate a UCG site have been shown historically to strongly influence not only the operational performance, but also the environmental performance of the site. Obviously, the feed rates and the substances fed to a gasifier will impact on the gas production rate, gas quality and the rate of coal consumption. However, the major operating issue that has arisen as a problem area in gasification operation has been the operating pressure. Excessive pressures have been linked to contamination of surrounding groundwater with organics by-products of the gasification process and reduced process efficiencies due to high product gas losses. The current best practice operating parameters that have been adopted in both Soviet operations and the more recent trials in the USA include ensuring that the gasifier operating pressure does not exceed the hydrostatic head pressure at the coal seam, thereby restricting the loss of product from the gasifier into the surrounding strata. Generally, this restriction has been found to improve both operating and environmental performance of the UCG sites. Other procedures were formally adopted in the USA as the Clean Cavern Concept, which also includes operating practices to ensure cleaning of organics from the cavity during the shutdown phase. The last of the government funded trials in the USA, Rocky Mountain 1, validated the use of these procedures and similar techniques are believed to have been successfully demonstrated during the Chinchilla trial in Australia.

1.4.5 Oxidant selection
UCG, like surface coal gasification, can use either oxygen or air as the feed gas. In surface gasifiers there has been a trend to use oxygen because the size of the gasifier can be reduced, with considerable savings in capital expenditure despite the requirement for an air separation plant. With UCG the expenditure on gasifier construction is relatively minor, so the use of oxygen will depend largely on the requirements for the product gas. Typically, low nitrogen dilution is required in synthesis gas, so oxygen would generally be preferred. In electricity generation processes the presence of nitrogen is not important if the gas calorific value is sufficient for use in gas turbines. Good quality air-blown UCG product gas will typically be acceptable, while oxygen-blown UCG product gas is likely to require dilution at the combustor in order to reduce the combustion temperature to the operating limit of the gas turbine. However, if carbon dioxide is to be removed from the gas stream it is better to have a low nitrogen stream and, therefore, oxygen is the preferred oxidant. There will be some differences in the design and operation of air and oxygen UCG systems. The metal components of an oxygen system must be of higher grades, but pipe diameters can be smaller and this reduces the cost of directionally drilled wells significantly. Operationally, higher temperatures are expected in oxygen-blown systems, so higher hydrocarbons are more likely to react to form simpler compounds and lower tar content in the product gas will result.
2 METHODOLOGY USED IN THIS STUDY

The site specific nature of underground coal gasification (UCG) processes requires that any study of the environmental impacts be referenced against a specific site and it is the aim of this study to provide a realistic analysis of performance of UCG at a representative site in Australia. There is a large degree of interaction between the process and the site, both from operational and environmental viewpoints, and this intimate linking between the site and the process provides specific challenges for understanding, managing and minimising environmental impacts and also for optimising the operation of UCG (Figure 2.1).

![UCG feedback loop diagram]

**Figure 2.1: UCG feedback loop**

The UCG process may continue for many years, and the environmental consequences may emerge for years after that. To develop an understanding of interdependencies over such long periods of time essentially requires modelling and prediction in a number of distinct topic areas. This study was performed in a number of stages that involved selection of a site, design and determination of the operating parameters for a UCG-based process, analysis of the impacts of the operation on the local, regional and global environment and consideration of the acceptability of this performance in the social and legislative environment in Australia. This section contains a brief summary of the methods used for these studies as an introduction to the more detailed analyses in subsequent sections.

2.1 Site selection

A previous study of the viability of UCG in Australia by Stewart (1984) estimated the resources of coal suitable for UCG in the major coal fields at that time. While this identified substantial resources, the coal industry has progressed since that time and it is considered now that the more suitable resources are in the relatively untouched fields, such as the Surat Basin. Given the untested nature of UCG, it would be more difficult to justify UCG in fields where the coal could be subject to conventional mining in the future. The Surat Basin was not considered by Stewart, as at the time of that study it was relatively unexplored, but it is now known to contain substantial reserves of high ash coal in thick seams that appear suitable for UCG operations. In order to limit the scope of the site selection study, the Eastern part of the Surat Basin was selected as being likely to provide a suitable site. A target coal deposit specification was developed based on the published experience of UCG worldwide and a preliminary analysis of characteristics that could be realistically expected in the region.
A regional resource model of the Eastern Surat Basin in Queensland was developed specifically for UCG project. This involved analysis of existing public data from petroleum and stratigraphic drill holes in the region in order to construct a 3-dimensional model of the basic sedimentary units (coal, sandstone, and heterolithic fine-grained rocks). In this framework, addition data from groundwater drill hole records was added to provide an overview of the hydrogeology of the region and regional structural and stratigraphic interpretations were made in the context of available drill hole geological and geophysical data. Any other available geophysical data (seismic, aeromagnetic and gravity) was added to the model to contribute to the understanding of the regional and local geology. This type of model varies somewhat from engineering models, as it is essentially an interpretation of the available data to generate an image of the geological situation that can be interrogated to provide data for other modelling activities. The model development relies heavily on the experience of the geologists involved, in this case drawing on the experience gained in the prior development of the Bowen Basin Supermodel and other coal geology studies in Australia. The Eastern Surat Basin model was used to select a site with suitable characteristics for UCG, based on past experiences, in the further analysis of environmental impacts.

2.2 Plant design and operation

The sizing and design of a UCG plant suitable for the selected site and prediction of the operational performance of the site requires the use of modelling tools developed in CSIRO. Several models have been developed to represent different aspects of UCG behaviour and, in combination, can be used to assist in the design and then predict performance in conjunction with experimental experience from previous UCG trials. These models are summarised below and the predictions of UCG performance are used as the input into the various environmental studies:

(a) Coal surface gasification model
A detailed model that represents the interactions of gas and coal in gasification and enables a fast and accurate method of evaluating changes in the behaviour of gasifiers when operating characteristics are changed. The input characteristics that can be changed include the ratio of water to coal, gas temperature, gas composition and coal characteristics. A full range of product gas properties, gas generation rates, water consumption rates and coal gasification rates are predicted by the model. This model was also used to assist in the preparation of correlations for use in the representation of UCG in the process simulation software, while a simplified version is used in the UCG cavity model.

(b) UCG cavity growth model
The core of the CSIRO UCG project has been development of a model that enables prediction of the operating performance of UCG sites. This has resulted in a 3-dimensional model called MISCGas, which predicts growth of an underground coal gasification cavity and the product gas composition during long-term UCG operations. A simplified version of the coal surface model that considers only the more significant parameters is included in the cavity model to predict the rate of cavity growth due to reaction of the cavity walls. This has been tested successfully against published data from experimental UCG trials; however there are very few trials that have sufficient published data to set all the required model parameters. Model performance is regarded as good for predicting product gas composition, but cavity shape prediction is less accurate for complex well arrangements. This is expected to have negligible impact on the large scale UCG modules in this study, as these have been designed with simple geometry for removal of large blocks of coal. The flexibility in cavity geometry is being addressed by combining the specialised code developed for UCG components into a general reactor code called KIVA, also written in FORTRAN, that has robust fluid dynamics, heat transfer and thermodynamics capabilities. In further studies it is intended that output from the geotechnical model be used to provide more accurate parameter settings for the cavity model in an iterative approach.

2.3 Greenhouse gas emissions

An important criterion in modern environmental analysis of fossil fuel plants is the determination of Greenhouse gas emissions, typically in comparison with existing or other prospective technologies. This is generally not considered explicitly in environmental legislation, but is an item of consideration during public consultation on new plant proposals. In this case, it was decided that the UCG process would be utilised for electricity generation using an available combined cycle gas turbine plant and the comparison of emissions would be against a similar plant using surface coal gasification to ensure that calculations are
on a common basis. A nominal electricity output of 400MWe was selected as being a scale that requires a full environmental analysis under Queensland legislation and that this size is a genuine commercial scale for electricity generation. However, while the gas turbine set is constant for all case studies, the actual output will vary depending on parasitic consumption of power in the plant and generation by the ancillary steam turbine set. Different power generation options using the same basic plant with modifications for carbon dioxide removal, with indicative economic analyses for the different plant designs.

This type of study is simplified by the use of simulation packages to estimate the thermodynamic performance of plant options. A commercially available simulation package called HYSYS.Process has been adopted for this purpose and allows the prediction of process properties, such as electricity generation efficiency, for systems involving complex arrangements of reactors, heat exchangers, pumps and turbines. The advantage of using this type of software is that the general reaction and thermodynamic components have been validated through prior testing, and plant configurations can be rearranged rapidly to assist in optimisation of the process under consideration. Some plant items are relatively novel and can be handled either by adding custom written modules to the models or manually inserting data from separate models. The gasification components were modelled in the simulation by using published data for the surface gasification cases and adding data prepared by the separate CSIRO models for the UCG cases. The modellng of the UCG is aided by analysis of the literature results of numerous (>50) underground coal gasification trials to ensure that input parameters for the CSIRO models, and the resultant output predictions, are consistent with expected behaviour for a UCG plant at the selected site. The other units of a standard combined cycle electricity plant are modelled using standard components of the simulation package; however, variants with carbon dioxide removal require other unusual components. Data for items such as shift reactors and carbon dioxide adsorption towers were also inserted manually into the simulations, with the data being prepared using separate models developed by CSIRO.

Output from the simulations and other models is used to specify the size and design of the components of the power plants and used in cost estimation. An earlier report by Beath (2003) outlined a methodology for estimating the design and cost of the UCG component of the process, which is customised for a particular site. Costing for novel items for carbon dioxide removal is reliant on models developed by CSIRO, but the other plant components are costed relative to published data for similar plant. While not an integral part of an environmental study, the economics of the processes are an important consideration and are strongly linked to the feasibility of Greenhouse gas reduction technologies.

### 2.4 Groundwater and subsidence impacts

There are two key items in analysis of groundwater impacts, namely the potential for depletion of regional groundwater supplies and the likelihood of significant contamination of groundwater in the vicinity of the UCG site (Mark and Beath (2004)). The issue of groundwater is also inherently linked to subsidence, as disruption of the strata above the gasifier is likely to result in increased permeability and water flow. Modelling of the impact of UCG therefore requires that two scales should be considered. The first involves detailed geotechnical modelling on a local scale of the UCG reactors and generates predictions of local disruption that can be input into a second model of the regional impact on groundwater.

The computer code used for the local geotechnical evaluation of UCG is COSFLOW, which has been developed within CSIRO Exploration and Mining as a tool to investigate stress, water and methane gas issues in longwall coal mining. The software provides predictions of subsidence due to the removal of coal and predicts the quantity of water flow into the cavity during operations, important factors in determining the environmental impact and operational performance of the UCG site. The code is a coupled mechanical and one or two phase fluid flow finite element simulator of deformation, stress and flow in a layered medium and is especially suited to coal measures. The mechanical component uses a Cosserat layered continuum approach, which is relatively efficient in accurately simulating the bending and fracture of bedded rock without the need for fine meshes that would make computer run times infeasible. The fluid flow component simulates conventional Darcy flow through the porous rock. Modeled mechanical failure induces permeability increases in the rock to simulate the effect of cracking,
and reconsolidation of the rock induces a permeability decrease. The water pore pressure from the flow component in turn modifies the rock failure.

Data on the growth rate and shape of the UCG reactors is input from the plant design and operating performance predictions. It is evident that this requires an iterative evaluation, as UCG operational performance is dependent on subsidence and water flow into the cavity. The modelling time involved in producing predictions is excessive and it is not practical to iterate the procedure, so assumptions were made regarding the operational performance and a subsequent phase of modelling would be required to re-predict all aspects of performance. It is unlikely that this will have a significant impact on the environmental aspects of the study, but an indicative impact of variations on operational performance of the UCG reactor on the electricity generation plant will be discussed. The geotechnical model has been validated against longwall mining operations, which have similar coal removal patterns to a large rectangular UCG module. An area of modelling that requires further research is the impact of high temperatures on the geotechnical properties, but this is expected to have small scale impact on roof collapse only. In the future it is also intended to include contaminant transport in the model to give a more detailed analysis around the cavity than is provided by the regional hydrology model.

Regional hydrology modelling involves uses of two linked commercial codes, namely MODFLOW and MT3D, for modelling the regional water flow and contaminant transport respectively. These codes are commonly used by hydrologists to simulate groundwater depletion through usage and the spread of contaminants resulting from underground tank leakage. MODFLOW simulates three-dimensional groundwater flow through a porous medium by solving the flow equation using the finite difference method. MT3D simulates the advection, dispersion and chemical reactions of contaminants in groundwater flow systems in either two or three dimensions. Input to the models is sourced from the data obtained in the regional geological survey, the local geotechnical modelling and the UCG operational performance analysis. The predictions of this modelling exercise are likely to be the most significant from a legislative viewpoint, as the impacts at and beyond the lease boundaries are generally used in environmental monitoring and reporting.

The computer code used in the local model has been used successfully to predict water flows into longwall mines and surface subsidence following longwall mining, but only when adequate data is available for calibration. The large extrapolation from longwall mining to UCG, the current lack of calibration data and the many uncertainties regarding model parameters, geometry and sequencing make the results reported here indicative of what may happen with UCG rather than predictive. The computer codes used in the regional models have been used extensively in groundwater studies for agricultural applications and, to a lesser extent, for mining. Again, the large extrapolation and lack of calibration data make results from this model indicative only. Both models, however, have shown themselves to be capable of prediction in other applications and, as uncertainties are reduced by fuller data acquisition and calibration is possible from preliminary trials, more accurate predictive modelling will be enabled.

2.5 Social and legislative issues

The introduction of a new technology such as UCG on a large scale can be the subject of much conjecture and analysis by both the public and legislative authorities. It is therefore important to ensure that the stages of developing a project are understood and data is made available so that a fair representation of the technology is given. Historically this involved ensuring that the legislative procedures to quantify environmental performance were correctly performed, but public involvement has become common for technologies that are unusual, particularly those utilising fossil fuels in novel ways, so both social and legislative issues are important to the environmental acceptability of the technology. Available literature was analysed to make an assessment of potential issues.

An indicator of social acceptability is obtained by performing public perception analyses. Public perception is currently identified as a risk to the economic and environmental viability of new technologies. In particular, perception of potential environmental impacts for new technologies is likely to provide a significant barrier to implementation, regardless of whether the true impact is larger than
impacts associated with other tried and tested technologies. To overcome this type of barrier it is necessary to have a process of social engagement in parallel to the environmental studies. An initial survey of public perceptions of UCG technologies was performed to gauge sensitivity of the public to implementation of the technology and to aid in the selection of methods that could be used for social engagement in the future. This study involved discussions with three focus groups from different backgrounds on the topic of UCG technology and the perceptions of social and environmental impacts of the technology.

Legislation, in particular environmental legislation, is a significant factor in gaining a licence to operate a new technology. A review of legislation that covers the use of UCG in the region of interest was performed with a view to comparing the likely performance of the process relative to environmental limits. A difficulty with this type of analysis is that the legislation was written without considering the possible introduction of new technology, so lacks clarity on the performance criteria that would be applied. It is likely that the emissions limits would be set for a particular development by negotiation with the regulatory authority, so this part of the study can only consider likely limits in comparison with the predicted performance of the plant.

2.6 Limitations of the research

The project is complex and the interdependencies between the site and the UCG process mean that any generic modelling will be limited in application to real situations. The specific properties that characterise any particular site will not be known accurately at this stage of a project and it is these properties that will determine the design of the UCG operation and the response of the site to that operation. Generic assessments such as the ones included in this project provide a powerful first step in developing the tools required to understand, manage and mitigate any environmental impacts. However, they contain uncertainties arising from a number of different sources:

- Scenario uncertainty regarding the scale and operation of the UCG site
- Lack of data, particularly regarding the geological structure and groundwater conditions
- Conceptual uncertainty regarding the geotechnical and hydrological response to UCG
- Future uncertainty about the length of operations, the success of remediation and prospective land use after the operation ceases

Nevertheless, the intent of the study is to provide an objective assessment based on the available best practice methodologies for this type of development. The results are aimed at providing a valuable indication of the sensitivities of the environment to a UCG operation and also an assessment of the magnitude of those responses. However, to develop greater levels of confidence about the impacts of UCG on the environment, further site characterisation and an iterative tuning of models would be required, preferably with some form of model validation to check that the models are adequately representing the behaviour of site and process in combination.
3 SITE IDENTIFICATION AND CHARACTERISATION

An analysis of the environmental impacts of underground coal gasification (UCG) must be related to a specific site, as this will influence the design and operation of the process. Therefore, it is necessary to identify a site that appears suitable for a UCG operation and then characterise this site so that further modelling studies can be performed on a realistic basis. This requires development of a preliminary set of site selection criteria that can be used to filter available coal resources as a method of eliminating unsuitable sites and assisting in the selection of a specific site for further analysis. A simplification was made to reduce the scale of the coal resource evaluation by assuming that a suitable site would be available in the eastern Surat Basin in Queensland, as the volume of geological data that needs to be examined for analysis of all Australian coal basins is excessive.

3.1 Site selection criteria

The site characteristics are extremely important to both the operational and environmental performance of UCG and, therefore, it is necessary to carefully select the site for any UCG operation. Previous studies in the Soviet Union (Skafa (1975)) and USA (Peters (1991)) have identified the key site characteristics required for successful UCG sites and these are discussed in Appendix A. Essentially, the UCG operation occurs with the geological surrounds representing the reaction vessel, so all attributes of the coal seam and adjoining strata can be considered as influencing the process. However, previous studies have found that only some of the geological properties have significant impact on the gasification process. These can be loosely categorised as coal seam, overburden and hydrology effects and the significance of these is summarised below.

3.1.1 Coal seam properties

There are a number of simple site criteria that are significant influences on the viability of UCG operations. Essentially, both the economic and technical viability of a UCG operation are strongly influenced by the coal seam thickness, depth and ash content. These are the major factors in determining the amount of drilling that is required to access a given volume of carbonaceous material in the coal seam. Water flow into the UCG operation is also a significant factor in determining the product gas quality, so can influence the suitability of a site for either technical or economic reasons, and discontinuities in the coal seam can affect the progress of gasification. Following is a brief discussion of how variations in each of these criteria affect the UCG process.

(a) Thickness

Coal seam thickness is both an economic consideration, as thicker seams allow access to more coal with less drilling, and a technical concern, as it affects heat loss during gasification, subsidence and the accompanied aquifer disruption. Soviet research (Skafa (1975)) indicated that it was possible to gasify coal in as thin as 1 metre thick seams; however, under the economic conditions prevailing at the time, UCG only become economically viable where the seam exceeded 8 metres in thickness. The definition of a coal seam for UCG operations may actually be comprised of several coal bands where the interburden between the bands is thin enough that the seams will link once collapse is initiated during gasification of the lowest band. No practical maximum thickness of seam has been identified, with seams in excess of 20 m thickness used at some of the more successful sites. A thickness of coal in combined seams of 10m or more has been targeted in this study, primarily to improve economics especially when drilling into deeper coals.

While the economics and operational performance of UCG are enhanced by use of thick coal seams, there are detrimental environmental impacts that should be considered. The collapse of overburden into the cavity created in a thick coal seam will have greater likelihood of causing subsidence at the surface, although this can be mitigated by the use of deeper coal seams, and is more likely to disrupt overlying aquifer systems, potentially leading to contamination issues. The overburden properties and site hydrological characteristics will have a substantial influence on these impacts.
(b) **Depth**

The coal seam depth has a number of different impacts on UCG operation and environmental impact. From an operational viewpoint, the maximum operating pressure of a UCG site is determined by the hydrostatic head at the coal seam and this is strongly influenced by the seam depth. For deep coal there is less likely to be a shortage of groundwater around the seam and the hydrostatic head is likely to have less significant change during operations, leading to increased operation stability and less risk of gas loss. The cost of drilling increases with depth and there is a practical limit to the capabilities of current drilling technology, with depths greater than 600m being problematic and expensive. In terms of environmental risk, subsidence at the surface typically decreases for removal of coal at greater depths and there is less likelihood of interfering with other users of the groundwater, either by contamination or depletion of water near the coal seam.

Selection of the depth of coal seam that should be targeted during site identification is complicated by the competing influences of economics, subsidence and groundwater impact. Also, there are different UCG reactor designs that can be used to minimise environmental impact for different sites, for example narrow cavities can reduce subsidence impacts for shallow UCG operations. The decision was made to target a site at 350 to 400 m depth for the primary reason that the operating pressure at this depth is sufficient to operate a combined cycle gas turbine plant without product gas compression being required. At these pressures there would be minimal modification required to use plant items developed for surface coal gasification processes with the UCG process. The depth proposed would be a relatively deep UCG operation as most operations of significant scale have been shallower than 200m with only relatively small trials being performed at depths greater than 300m. Technically, current drilling technology is suitable for these depths, as UCG trials at depths of greater than 600m have demonstrated, and coal of this depth is often targeted in Australia using similar drilling techniques for coal bed methane extraction. There are a number of advantages associated with the use of deeper coal seams, including:

- **Smaller relative change in operating pressure with time** – There is less change in hydrostatic head with time due to the increased area for replenishment of the water table above the UCG site and this can improve the operating performance of both the UCG reactor and surface plant.
- **Reduced environmental impact** – Deeper groundwater is less likely to be extracted for surface use, so if contamination occurs it will have less significance. Maintaining a higher water table will also reduce the potential for damage to surface vegetation and gas leakage.
- **Improved product gas quality** – An increase in the operating pressure results in more intense gasification conditions with higher temperatures, and this leads to a higher quality product gas with less tar components and higher calorific value after cleaning. This advantage increases with the use of oxygen rather than air and results in lower carbon dioxide emissions from the process, an important environmental factor due to the Greenhouse gas effect.
- **Higher process efficiency** – The higher product gas pressure makes the gas suitable for use in the process without further compression. The feed gas must be compressed more for the deeper operation, but this is a smaller volume flow than the product gas, is at room temperature and the energy that can be recovered from the product stream is greater than the energy expended in feed compression.
- **Smaller wells** – Due to the higher pressure there is a smaller volume flow of feed and product gas for the same capacity of UCG site and smaller wells can be used, with a cost reduction that can partially or fully compensate for the increased costs with greater depth and pressure. This can also justify the use of oxygen, which has about 20% the volume of air for the same plant capacity, but note that higher-grade materials are required in the wells for oxygen feed.

(c) **Ash**

Coal ash content has been shown in Soviet research (Skafa (1975)) to be of only minor significance in the performance of UCG operations, with no discernable decline in performance for ash content up to 40%. In theory, increasing ash content should reduce performance because of the energy consumption involved in heating the ash up to the operating temperature of the gasifier. However, the ash will also cool again as the gasification front moves through the coal seam and some of this energy will be recovered in the product gas. Very high ash content is likely to prove a hindrance to gas flow and this may be the cause of
the decline in performance noted where ash content exceeds 40%. The lack of sensitivity to ash content has resulted in UCG being suggested as an utilisation technology for high ash coal seams, which are often difficult to mine economically using conventional techniques.

(d) **Discontinuities**

One of the key requirements of UCG is that the coal seam be essentially free of significant discontinuities, such as faults. Minor disruptions to the seam can be acceptable, but major breaks in the coal will lead to difficulties in getting gas flow through the coal and can lead to high gas leakage rates from the UCG cavity. If the discontinuities are identified in the site characterisation and are sparsely distributed, it may be possible to design the UCG layout to minimise the impact on operations. There are potential environmental issues from the discontinuities, as there is increased risk of leakage of contaminants from the site.

(e) **Rank**

Coal rank has been the subject of some examination during previous UCG research activities. Soviet researchers experimented on all ranks of coal and found little sensitivity to rank (Skafa (1975)). The USA researchers concluded that high rank coal was difficult to ignite and that swelling bituminous coals required careful design to limit the risk of blockages occurring (Peters (1991)), however this appears to have been theoretical conclusions rather than Soviet conclusions based on practical experience. Another potential issue is that low rank coals tend to have excessive moisture content that will impact on UCG performance. In the region of interest for this study the coal rank is typically high volatile bituminous with minimal swell, which classes it as suitable for UCG.

3.1.2 **Overburden properties**

The strata overlying the coal seam have two effects on gasification. Firstly, they can provide water that flows into the gasification void and, secondly, they will collapse into the void when thermally damaged and insufficiently supported. Soviet research (Skafa (1975)) suggest that the ideal roof strata is of low permeability, preferably lower than the permeability of the coal itself, so that water ingress from the roof will be minimal and gas escape unlikely. In addition, it is preferred that the roof material swell when heated and break into small pieces to fall at a stable and slow rate. Some materials, such as mudstone or siltstone, may fuse on heating to provide stronger and less permeable overlying strata that would be beneficial to the process.

There can be distinctly different forms of undesirable behaviour resulting from roof material that is unsuitable. Material that is not significantly affected by heat and a lack of support can result in excessively large cavities, into which injected gases diffuse to the extent that they have negligible reaction with the coal or char. In contrast, fragile material that collapses easily can result in blockage of injection and production pipes or even fill the gasifier void itself. Another possibility is that a zone of high permeability will occur in the overlying strata and gas flow will bypass the coal containing regions, leading to un-reacted oxygen entering the production pipe. Excessive disruption of the overlying strata can also lead to disruption of aquifer systems, resulting in mixing of different quality water and possible contamination of clean groundwater bodies.

It is also desirable that the overburden behaviour be predictable during UCG operations. The design of a UCG site relies upon assumptions regarding the rate of collapse of the overburden. Excessive variability in collapse characteristics during operation could lead to large fluctuations in gas quality and production rate. For this reason it is best to avoid sites with overburden that is heavily faulted or consists of unconsolidated materials of varied composition.

3.1.3 **Hydrology**

Water is essential to the operation of a high efficiency UCG process, as it provides a seal around the gasification cavity that limits escape of gas and the correct quantity participating in the reactions results in higher quality product gas. The operating pressure of a UCG reactor should be kept lower than the hydrostatic head at the seam, so water will flow into the cavity continuously and sufficient groundwater should be available to maintain this flow without depleting the site water resources excessively. The
availability of water at a site is influenced by the depth of the subject coal seam and the permeability of the materials around the UCG reactor, so these are key issues in the selection of a site. Low permeability overburden is preferable to reduce the risk of flooding of the cavity during operations.

The presence of clean waters close to the coal seam raises the issue of potential groundwater contamination. This can occur due to operational problems forcing pyrolysis products from the affected coal into aquifers, but is more likely to be a serious issue if aquifers are disrupted due to subsidence in the vicinity of gasifier void. This can lead to clean waters mixing with those directly in contact with heat-affected coal or possibly flowing through the coal. At sites where water is extracted for domestic or agricultural use from the vicinity of the coal seam, it is likely that the site would be deemed unsuitable for UCG by local authorities. Therefore, sites with poor quality groundwater are preferred for UCG operations, regardless of other controls that may be used to limit the risk of groundwater contamination.

3.1.4 Summary of desired site characteristics

In summary, the characteristics that are desirable for a UCG site are:

- Coal seam >10 m thick
- Ash content <40% (ad basis)
- Rank less important, although low rank coals may have high moisture and high rank may be hard to ignite
- Well-defined seam with minimal discontinuities
- Seam dip <20°
- Depth 300-400 m with high hydrostatic head
- Overburden with low permeability that is structurally sound
- No good water aquifers in vicinity
- Surface suitable for low impact use and some subsidence
- Scale of deposit matched to economics of utilisation (eg power plant size)

These characteristics are a starting point for identification of a suitable site and the details of a specific site are required in the site design and risk management strategies.

3.2 Surat Basin assessment

Using the site selection criteria as a starting point the eastern margin of the Surat Basin was chosen as the study area for UCG site selection, as shown in Figure 3.2. There are two major reasons for this selection, namely, this area has large reserves of deep high ash coal that is unlikely to ever be mined with conventional techniques and a successful UCG trial has already been conducted at Chinchilla, so the Surat then is more likely to be utilised for UCG in the short term than any other coal basin in Australia. The aim of the Surat Basin assessment is to try to find an “ideal” site or to at least determine the likelihood of an ideal site existing in the Surat Basin.

An initial review was undertaken using GIS to compile a number of data sets including cadastral data, topographic maps, satellite imagery, land use, existing petroleum and coal exploration permits and leases and basic resource information taken from publicly available bore hole data. The Queensland Department of Natural Resources, Mining and Energy suggested that CSIRO should also apply for Exploration Permits over the most likely areas to allow us to set aside areas for field investigations in the future. This was done and the EPCs are shown on Figure 3.3.

The area considered prospective based on a first pass assessment of the depth to coal measures is bounded by the two thicker black contour lines which delineate a minimum and maximum feasible depth to the coal bearing units. Coincidentally this is also the area which has been identified as having potential for coal seam gas extraction, and has been the subject of explorative drilling by companies in recent years.
3.2.1 Basin Overview
A detailed analysis of the regional geology has been reported by Sliwa and Fraser (2004) and the following is a brief summary of their study.

(a) Geology and structure of the study area
Five sedimentary cycles have been identified in the Surat Basin succession, each starting with the deposition of a sandstone rich unit (regional aquifers) with an erosional base. Each cycle has an upper unit that is finer grained and more complex in its lithologies (regional aquicludes). However these units may contain significant local aquifers. The downcutting of aquifer units into the aquicludes may provide significant interconnectivity for groundwater movements.

The major structure in the study area is the Moonie-Leichhardt thrust system, which is a deep crustal fault with multiple episodes of reactivation during and after deposition of the Surat Basin succession. Additional smaller scale structures should be expected near the Moonie-Leichhardt fault system, particularly along the extension of the graben. Mild faulting in other parts of the study area does not follow a pattern that can be used for further fault prediction.

(b) Characterisation of Walloon Coal Measures
The coal measures contain 4 economic coal-rich intervals, which are progressively cut out to the south by the disconformity at the top of the coal measures. Individual coal seams and even clusters of coal seams cannot be correlated regionally at the present spacing of petroleum exploration wells (1-20 km). In order to characterise a potential UCG site in detail, exploration drilling of less than 1 km spacing would be needed to allow correlation of individual coal seams and interburden lithologies. Coal seams are generally more abundant and thicker in the northern part of the study area, as well as in the upper coal-rich intervals.

The known coal deposits in each coal-rich interval record a gradual change in coal seam geometry. The lower interval (Millmerran) has the most regionally continuous seam, the middle intervals (Onaview, Wilkie Creek) are characterised by abundant splitting and coalescing of seams, while the upper one (Austinvale) forms pods of coalesced seams separated by coal-poor, sandstone-dominated channel facies (Figure 3.3). Apart from the Austinvale coal deposit, which occurs to the north-west of the study area, the “pod-like” outlines of the known coal deposits are created by erosion from modern river systems. More detailed characterisation of each of the coal-rich intervals in the Walloon Coal Measures could be achieved by a reinterpretation of exploration data from the known coal deposits in the region.

(c) Hydrogeology of the Study Area
The Study Area (as detailed and shown on Figure 3.1 and Figure 3.2) occurs on the eastern margin of the Surat Basin. Figure 3.4 details the solid geology over the Study Area and on this figure the regionally significant aquifers are also shown. It is important to note that, with respect to the Walloon Coal Measures, the stratigraphically younger and regionally significant Mid Jurassic to Cretaceous aquifers (Springbok Sandstone, Gubberamunda Sandstone, Mooga Sandstone, Bungil and Grimau Creek Formations) all occur west of the sub-cropping Walloon sequence. The stratigraphically older Hutton Sandstone, which is a major regional aquifer, outcrops to the east of the Walloon Coal Measures and the older still Precipice Sandstone (also a significant aquifer) does not outcrop but it abuts basement in the sub-surface on this eastern margin.

A database of waterbores within the study area was received from the Queensland Dept of Natural Resources and Mines. This database contained water chemistry, and water level measurements, most of which were collected at the time the waterbore was drilled; however, some were collected as part of more recent studies and subsequent monitoring. Of the approximate 5000 waterbores that cover the area, only ~1000 penetrate beneath the quaternary alluvials into underlying lithologies.

Despite an apparent abundance of data, there is very little usable hydro-geological information suitable to assist in developing an understanding of the local groundwater condition and characteristics that may
assist in developing an understanding of a specific UCG site. This is due to the majority of the data being approximate, and often incorrect, logging from water bores. It is recommended that discussions/negotiations be held with companies and organisations that may hold information relevant to assist in our understanding of the local and district groundwater regime in the area with the view to increased understanding through co-operation. A more detailed investigation focussed on specific sites would be needed to understand specific UCG sites to gauge the potential impacts of the local groundwater hydrology.

(d) **Groundwater Quality and Use**

Groundwater quality in the target area is highly variable with the majority of water resources suitable only for stock water. Salinity and dissolved solids are high in most aquifers. Locally however there are some good quality water resources, and the major aquifers such as the Springbok Sandstone contain large quantities of water of reasonable quality. Spatial and temporal variability in the historical water quality data is high and any large project in the region will require site specific background assessment to determine the acceptable criteria for water quality protection. Water usage is an issue in areas where local graziers rely on ground water to supplement surface water for stock watering and is an important issue for prospective UCG or coal seam methane projects in the area.
Figure 3.1: Regional view
Figure 3.2: Overview of target UCG area
Figure 3.3: Coal bearing intervals of Eastern Surat
Figure 3.4: Solid Geology of Eastern Surat
3.3 Selecting a representative UCG site

The purpose of this section is to suggest an area suitable for modelling the hydrogeological impact of a potential UCG operation, based on the availability and representativeness of data for a representative UCG site in the study area. The site was selected based on an approximate match to the criteria listed earlier in this section. The main issue with building a detailed model from existing data is the wide spacing of the petroleum exploration wells in the study area compared to the scale of a potential UCG site. So the area chosen for the conceptual model was driven as much by data availability as by the most prospective geology. The data that is publicly available for the Surat while voluminous does not in most cases contain enough detail at a sufficient resolution to develop a detailed and site specific structural model. However, this is planned as part of the next phase of research as more data becomes available to the project team. Instead, a generic model was constructed based on data from a borehole for which detailed geological data was available.

The final choice focussed on the area around well 50207 (Southeast Teatree 1, Figure 3.5 a,b,c). This well contains an interval of approximately 10m of coal spread over a 16m interval at a depth of ~390 m. These coal seams are equivalent to the seams mined at Wilkie Creek only 20 km to the northeast. Well 50207 only penetrates part of the Walloon Coal Measures, but has very detailed geophysics allowing reliable lithological interpretations. The closest nearby borehole is well 1431, which lies about 1.3 km to the northwest. This well has less detailed data, but penetrates the entire Surat Basin succession. Comparing the coal seam distributions across the two wells highlights their variability even at local scale, with no confident coal seam correlations possible between the two holes. Further exploratory work in the area would be required to accurately quantify the extent of the thick coal resource.

The data from well 50207 forms the basis for the groundwater modelling discussed in subsequent chapters, with certain information estimated from the experience of the geologists (eg. porosity, permeability and etc.)

Figure 3.5: Detail of Sample Bore Location
4 SCENARIO DEVELOPMENT

In order to address the interdependencies between UCG operations and site characteristics in a necessarily generic modeling exercise, a scenario approach was taken. Environmental performance was simulated using a base scenario. Where predictions are at variance with the initial assumptions it will be necessary to assess the impact of the variance on the validity of the predictions. For example, prediction of gasifier performance requires estimates of water flow into the reaction zone and the predicted product gas characteristics are used to estimate the required coal consumption for the desired electricity output, however the coal consumption rate is in turn used in the geotechnical and hydrology modeling as input to predict, among other predictions, the water flow into the cavity. Variations between the assumed and predicted values for any variables in this loop will impact on all predicted variables, possibly significantly.

There are several considerations in selecting a coal deposit for UCG use, namely:

- Cost
- Operating pressure
- Groundwater availability
- Subsidence

Typically, a shallow site will be less expensive to establish due to the reduced costs in exploration, drilling the process wells and monitoring the gasifier. However, the performance of gasification and power generation systems is strongly influenced by operating pressure, so an operating pressure of between 20 and 30 atmospheres is typically used in surface plant. At lower pressures the product fuel gas must be compressed if it is to be used in a gas turbine system. By operating at greater depth there is also a reduced risk of depleting the groundwater supplies above the coal seam and subsidence at the surface will be reduced. It is unlikely that a quantitative optimum can be found given the disparity and complexity in the factors considered, so a fairly arbitrary decision was made to aim for a coal seam depth of 350-400m for the site. The cost and performance of UCG is also strongly dependent on the thickness of the coal seam, with thicker seams being preferable due to less drilling being required and lower heat losses per unit of coal consumed. A target seam thickness of 10m or greater of coal was specified in the geological analysis.

4.1 Location for UCG site

In order to constrain the modelling and also to provide a common link between the different modelling tools, a central scenario for the UCG process was identified based on a geological structure derived from a reasonably typical location for a UCG process. The central scenario assumes that UCG is to be undertaken in the Surat Basin using coal measures that are potentially suitable for UCG and are currently being explored for coal seam methane, but are not economically mineable with conventional mining techniques due to the high ash content. The area is relatively close to electricity infrastructure. A typical geological sequence was identified from data in a borehole (well 50207) by Sliwa and Fraser (2004). The geological strata used in the modelling are listed in Table 4.1. It is assumed that underground coal gasification occurs in coal seams located approximately 395m below the surface at the selected site. The stratigraphy is known to be quite variable in this area (Sliwa and Fraser 2004) and the details of the strata thicknesses may differ significantly at other locations. Typical data on geotechnical properties, such as permeabilities, for the formations listed are available for the region for use in the geotechnical and hydrological analyses, which will include some analysis of the sensitivities to variations in the values used. The coal measures identified are closely spaced and constitute a single seam of approximately 10m thickness of coal for the purpose of UCG.
### Table 4.1: The geological formations included in the base case models

<table>
<thead>
<tr>
<th>Formation name</th>
<th>Thickness at well 50207</th>
<th>Common rock types</th>
<th>Estimated permeability measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Westbourne formation</td>
<td>287m</td>
<td>Siltstone, mudstone, fine quartzose to labile sandstone</td>
<td>Low</td>
</tr>
<tr>
<td>Springbok sandstone</td>
<td>33m</td>
<td>Sandstone, siltstone, mudstone and some coal</td>
<td>High</td>
</tr>
<tr>
<td>Upper Walloon coal measures</td>
<td>65m</td>
<td>Lithic sandstone, siltstone, mudstone, coal</td>
<td>Low</td>
</tr>
<tr>
<td>385 and 390 coal measures</td>
<td>10m</td>
<td>Coal</td>
<td>Medium to high</td>
</tr>
<tr>
<td>Lower Walloon coal measures</td>
<td>165m</td>
<td>Lithic sandstone, siltstone, mudstone, coal</td>
<td>Low</td>
</tr>
</tbody>
</table>

#### 4.2 UCG design

The design of UCG plant is aimed at minimising the variations in operational output that arise from changes in the reactor operating conditions due to roof collapse and cavity size, preferably while obtaining the highest product gas quality possible. A large number of UCG designs have been trialled in the past, with a selection of these being discussed in Appendix A, and the suitability of these for a particular operation being determined largely by the site characteristics.

Given the depth of coal seam targeted, the use of directional drilled wells is preferable to reduce the amount of drilling required to access the coal. By using multiple parallel wells in a UCG module, with alternate wells serving as injection and production wells, a rectangular block of coal can be delineated for gasification and progress of the gasification front can be controlled by individual adjustment of flow rates for each well. In this manner a reaction front of relatively constant area can be maintained during the life of the module. The proposed design of a UCG plant using directionally drilled wells and based on conservative current drilling technology is depicted in Figure 4.1. Vertical wells are used at the end of the directionally drilled wells to assist in ignition and drainage of surplus water. Based on a coal seam depth of 395m it is expected that a length of 600m of horizontal in-seam well can be readily achieved and, with a spacing of 30m between each well, approximately 1 million tonnes of coal can be accessed per module for a 10m thick coal seam. Subject to operational requirements, it is expected that a module would have an operational life of between 2 and 3 years.

![Figure 4.1: UCG module design](image)

A preliminary estimate of operational performance of a UCG module was made using the CSIRO models for oxygen blown gasification and past experimental results for UCG trials, notably the Rocky Mountain 1
trial in the USA. The quantity of water participating in the reactions or evaporating was estimated using data from the Linc Energy trial at Chinchilla, which used essentially the same coal seam, but at a shallower depth. The characteristics of gasification and the product gas predicted are given in Table 4.2 for what is considered a conservative estimate of the most likely conditions at the site.

Table 4.2: Characteristics of the clean fuel gas and preparation for IGCC case studies

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Units</th>
<th>Good case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen (95mol%) required</td>
<td>kg:m(^3) clean gas</td>
<td>0.394</td>
</tr>
<tr>
<td>Coal consumed</td>
<td>kg:m(^3) clean gas</td>
<td>0.446</td>
</tr>
<tr>
<td>Water used</td>
<td>kg:m(^3) clean gas</td>
<td>0.352</td>
</tr>
<tr>
<td>Raw gas</td>
<td>m(^3):m(^3) clean gas</td>
<td>1.327</td>
</tr>
<tr>
<td>Condensate removed</td>
<td>litres:m(^3) clean gas</td>
<td>0.242</td>
</tr>
<tr>
<td>Particulates removed</td>
<td>mg:m(^3) clean gas</td>
<td>6.36</td>
</tr>
<tr>
<td>Pressure</td>
<td>kPa</td>
<td>2760</td>
</tr>
<tr>
<td>Temperature</td>
<td>°C</td>
<td>45.00</td>
</tr>
<tr>
<td>Calorific value</td>
<td>MJ/m(^3) (HHV, 25°C, 1atm)</td>
<td>11.45</td>
</tr>
<tr>
<td></td>
<td>MJ/kg (HHV, 25°C, 1atm)</td>
<td>11.91</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>Volume%</td>
<td>31.40</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>Volume%</td>
<td>28.80</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>Volume%</td>
<td>25.98</td>
</tr>
<tr>
<td>Methane</td>
<td>Volume%</td>
<td>10.54</td>
</tr>
<tr>
<td>Ethane</td>
<td>Volume%</td>
<td>0.75</td>
</tr>
<tr>
<td>Hydrogen sulfide</td>
<td>Volume%</td>
<td>0.01</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>Volume%</td>
<td>2.03</td>
</tr>
<tr>
<td>C:H ratio</td>
<td>Molar ratio, dry gas</td>
<td>0.610</td>
</tr>
</tbody>
</table>

Based on the predicted gasifier performance, an estimate of power generation at 45% efficiency from the product gas using a combined cycle gas turbine plant and data from previous trials, a series of assumptions were generated for use in the geotechnical and groundwater modelling as shown in Table 4.3. This establishes coal consumption rates and assumes the quality of cleaning of the cavity at completion of the module gasification. Contaminants are taken as two distinctly different materials. One is the inorganic salts that have been concentrated during operation due to evaporation of water, represented as total dissolved solids (TDS). The other as an organic contaminant, taken to be benzene due to this being the most evident compound from the contamination that occurred at the Hoe Creek II and III sites in the USA. A single refill and flush of the cavity is taken as the cleaning procedure at the end of the module life and the concentrations of the contaminants are representative of only a minimally effective cleaning procedure.

Given the scope of the gasification process, a total of three modules are required to be in operation simultaneously and a worst case layout for impact on groundwater and subsidence is shown in Figure 4.2, showing each module as a rectangle of affected coal. These are oriented 30° east of north and aligned with the maximum dip direction at this location, with the gasification proceeding in the up-hill direction. The gasification is assumed to be simultaneous in each cavity, with the gasification proceeding at approximately 0.7m/day, taking 2.3 years for the 600m long cavities. Due to the close spacing of the modules this design will have an exaggerated impact on the local groundwater supply and any interaction between the modules due to inadequate pillar sizing will results in higher levels of subsidence. The geotechnical modelling study will consider the sensitivity to this arrangement relative to a more logical spacing where the modules are spaced more widely during operations. It is also logical to operate the modules at staggered stages of completion in order to avoid having simultaneous starting of multiple replacement modules on completion; however this proved difficult to model in the geotechnical and hydrology packages. This is not expected to have significant impact on the predictions.
Table 4.3: Site assumptions for the geotechnical and groundwater studies

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal depth (bottom of seam)</td>
<td>395 m</td>
</tr>
<tr>
<td>Coal seam thickness</td>
<td>10 m</td>
</tr>
<tr>
<td>Coal seam dip</td>
<td>2°</td>
</tr>
<tr>
<td>UCG modules operating</td>
<td>3</td>
</tr>
<tr>
<td>Module length</td>
<td>600 m</td>
</tr>
<tr>
<td>Module width</td>
<td>180 m</td>
</tr>
<tr>
<td>Pillar between modules</td>
<td>60 m</td>
</tr>
<tr>
<td>Module life</td>
<td>2.3 years</td>
</tr>
<tr>
<td>Total coal consumption</td>
<td>1,407,818 t/yr</td>
</tr>
<tr>
<td>Coal consumption per module</td>
<td>469,272 t/yr</td>
</tr>
<tr>
<td>Total groundwater consumption</td>
<td>1,055,864 t/yr</td>
</tr>
<tr>
<td>Groundwater consumption per module</td>
<td>351,955 t/yr</td>
</tr>
<tr>
<td>Contaminated water volume left in cavity at shutdown</td>
<td>231 m³/module</td>
</tr>
<tr>
<td>Concentration of benzene in contaminated water</td>
<td>100 µg/litre (100 ppb)</td>
</tr>
<tr>
<td>Total dissolved solids (TDS) in contaminated water</td>
<td>1400 mg/litre (1400 ppm)</td>
</tr>
<tr>
<td>Assumed concentration of benzene after cavity re-filling</td>
<td>10 µg/litre (10 ppb)</td>
</tr>
<tr>
<td>Assumed TDS after cavity re-filling</td>
<td>1400 mg/litre (1400 ppm)</td>
</tr>
</tbody>
</table>

Figure 4.2: Plan view of cavity layout for three modules in the base case analysis
4.3 Site closure

Typically it would be expected that an electricity generation operation of the scale considered in this study would operate for a minimum of 25 years before closure and the resource selected in this study would be sufficient for a considerably longer operation. To model this length of operation would be extremely difficult and would be unnecessary for most aspects of the process. The exception is the study of groundwater impacts; however the trends can be established based on analysis of the behaviour of the single set of modules described above during operation and after shutdown. This is still a lengthy modelling process covering several years of operation, site clean-up and post-operation.

The scenario developed for the analysis is to consider that a two year period after the module had been gasified would be used to clean the cavity according to the principles of the Clean Cavern Concept developed from the USA trials. This would involve a slow depressurisation of the cavity, followed by natural refilling with groundwater. The intent of this process is to firstly attempt to reform any organics in the coal or rock around the cavity into simpler compounds using steam formed as water flows into the hot region around the cavity. Once the site cools, the water flowing back into the cavity should carry most of the residual organics back into the cavity. Once the cavity is refilled, the water and contaminants are pumped out for treatment on the surface and the cavity is again allowed to refill. The pump out, treat and refill procedure is repeated until the water in the cavity is of acceptable quality. Previous experience with this technique is limited to the Rocky Mountain 1 trial in the USA and Chinchilla in Queensland, but has indicated that a single refill, pump and treat are likely to be sufficient. For the purpose of this study, this is taken as the only treatment and residual levels of contaminants after the first flush of the cavity were estimated based on compositions from the Rocky Mountain 1 and an assumption of a poor quality clean, as given in Table 4.2. The quantity of this contaminated water was taken as filling the cavity.

Organic and inorganic contaminants were assumed to behave differently after the clean-up process, with the inorganic contaminants being diluted by groundwater flow through the cavity while organic contaminants were assumed to stay at constant levels within the cavity indefinitely. This was assumed to be due to different mechanisms being responsible for the contamination. Inorganic contaminants were assumed to be concentrated during gasification due to evaporation of the water, so are not renewed on dispersal. The organic contaminants are assumed to be sourced from residual tars that were not decomposed or pumped out during the clean-up, so will continue to supply low levels of soluble components after operations ceased. These would theoretically decline in concentration with time, but for the purposes of the analysis as a worst-case situation are taken to maintain the levels in the cavity indefinitely.
5 GREENHOUSE PERFORMANCE

5.1 Ramifications of Greenhouse gas emissions

Greenhouse emissions from new electricity generation plants are not specifically included in current environmental legislation in Australia, but are of public interest and have become an issue for environmental lobby groups. This has an impact on the political process for environmental approvals, as has been shown by the NSW government refusal to allow the second stage of Redbank Power Station to proceed in the Hunter Valley. There are two reasonably clear targets for emissions if a new electricity generation plant is to have advanced environmental performance; as a bare minimum it should have lower emissions than current coal-fired plant, but it is preferable that it should have lower emissions than conventional natural gas fired plant. This second target is not strict, as natural gas has restricted supply in many parts of Australia and, therefore, is not a real option for new power plants. However, it is a reasonable target for emissions, given the higher acceptability of natural gas for power generation. It is unlikely that a plant with higher Greenhouse emissions than current coal-fired plant will be approved regardless of other environmental and economic advantages.

There have been prior publications that address the issue of Greenhouse emissions from UCG, notably Davis and Kendrick (1999) and CISS (2001). The CISS (2001) study was part of a comprehensive life cycle analysis of different electricity generation techniques and the UCG process was based on air-blown experimental results from the Linc Energy Chinchilla trial. The power system considered in this case was a combined cycle gas turbine power plant with heat recovery steam generation and a steam turbine. Results from the study are summarised in Figure 5.1 and indicate that the UCG process would have lower Greenhouse emissions than existing coal-fired power generation technologies. The coal-fired technologies that are indicated as having lower emissions are not currently in commercial operation and mostly involve removal of carbon dioxide for sequestration. The air-blown UCG process is not particularly well suited to carbon dioxide removal due to the large volume of gas that needs to be processed. However, oxygen-blown UCG at higher pressures would be expected to have similar requirements to IGCC plants for carbon dioxide removal and could be an alternative approach to low emission electricity generation. The Davis and Kendrick (1999) study was for an oxygen-blown UCG process with a combined cycle power plant and gave similar emissions figures to oxygen-blown IGCC processes utilising similar turbine systems.

The other important factor in the implementation of new technologies is the cost of electricity production. While not directly related to the Greenhouse gas emissions, it should be recognised that carbon dioxide removal adds a major capital and operating expense to the plant. So, if this approach is to be taken to reduce Greenhouse emissions, it requires that the total cost of electricity production be comparable to other low emission technologies, such as renewables or natural gas combined cycle. Both CISS (2001) and an earlier Flagship report (Beath (2003)) have indicated that UCG has the potential for electricity generation at a cost comparable to large-scale conventional coal-fired power stations and significantly cheaper than IGCC plants. This suggests that if carbon dioxide removal for sequestration can be applied in an effective manner nearby, then UCG would be a cost effective method of significantly reducing Greenhouse gas emissions.
5.2 Life cycle analysis versus plant emissions only

In some recent studies, for example the CISS (2001) study, Greenhouse emissions are determined on a life cycle analysis basis. This includes an estimate of the Greenhouse emissions involved in ancillary operations, such as constructing the plant, mining of the coal, mine waste oxidation and transporting of coal to the plant, against the total electricity production over the entire plant life. This can be a useful exercise in revealing discrepancies between the reported plant emissions and the ‘true’ performance of a process with regard to Greenhouse performance. Typically, this type of analysis is used to show the real Greenhouse impact involved in using natural gas that had naturally high carbon dioxide content that was vented in processing or had passed through leaking pipelines. However, these are extreme cases where the emissions for life cycle analyses are much higher than the plant emissions. With coal fired processes the life cycle analysis is typically only a few percent higher than the plant emissions. With coal fired processes the life cycle analysis is typically only a few percent higher than the plant, for example the CISS study showed that 97% of the emissions were from combustion of coal in conventional coal power plant (or 96% for a surface gasification IGCC system). The error involved in neglecting the non-plant emissions is therefore negligible in the context of an evaluation of hypothetical plants and only plant emissions will be considered in this study. It would be expected that a full life-cycle analysis would favour UCG processes slightly due to reductions in construction and transport emissions.

5.3 Electricity generation technology

The issue of Greenhouse gas emissions from fossil fuel electricity generation plants has resulted in renewed research efforts aimed at improving the technologies for power generation. For coal fired plants there are essentially two different approaches to this, namely to either increase the efficiency of electricity generation or to incorporate a carbon removal stage in the process to reduce carbon dioxide emissions. The product gas from UCG is expected to be suitable as a substitute for mined coal used in surface reactors in some processes, but differences in the characteristics are likely to impact on operations.

Historically, the improvement of power station efficiency has been driven by a desire to reduce fuel consumption and, thereby, reduce the cost of production of electricity. Typically, this results in an
increase in plant capital cost and it a balance between fuel and capital costs that has determined the type of power plant that is constructed. In more recent history there has been more incorporation of environmental requirements into this decision making process and this has resulted, in some countries, in the development of coal gasification technologies to reduce sulfur emissions. Gasification also allows coal power plants to take advantage of the improvements in gas turbine technology that have the potential to significantly improve the efficiency of electricity generation. Coal gasification for power generation is commonly referred to as integrated gasification combined cycle (IGCC), because there are significant efficiency gains in integrating the gas turbine shaft output with other plant items to reduce generator losses. Uptake of IGCC worldwide has been slow, in large part due to high capital cost, but also due to the efficiency gains being lower than originally anticipated. The issue of sulfur emissions is generally handled by switching to lower sulfur coals or by flue gas desulfurisation with conventional boiler/steam cycle plant.

The inclusion of carbon dioxide removal is difficult to justify in practice due to the lack of legislative requirements for Greenhouse emissions in most countries and the high capital and operating costs involved in adding plant that is also likely to have a negative impact on electricity generation efficiency. Currently, carbon removal is a research topic, rather than an expected inclusion in new power plant. Research is currently focussed on the best methods for incorporating carbon removal in advanced technology power plants to minimise the cost and efficiency drop. Most researchers favour modified IGCC processes, because the carbon can be removed from a pressurised stream with low nitrogen dilution. The technology also exists to convert carbon monoxide to carbon dioxide for removal from fuel gas, enabling the production of high hydrogen content streams. This is the target of research programmes worldwide, but the technology for utilising the hydrogen stream is less well established as it is not suitable for currently available gas turbines and fuel cells have not achieved the scale or reliability required. Conventional boiler plant is not readily adapted to carbon removal, as the carbon would be removed from approximately atmospheric pressure flue gas with high nitrogen content, resulting in considerable energy consumption and reduction in power plant output. Other configurations of combustion can be used to produce concentrated carbon dioxide streams, but they are expected to have lower electricity generation efficiencies than the modified IGCC processes, if suitable gas turbines can be developed.

In view of this background, it appears that the most likely application for UCG product gas in power generation will be as a substitute for surface gasification, with or without carbon removal, in IGCC plants. For this reason, the performance of UCG will be referenced to the performance of a conventional surface gasifier in similar power generation systems for this analysis. The basic block process diagram for an IGCC plant is shown in Figure 5.2. The main unit processes are the same for the use of either surface or underground coal gasification as oxygen-blown processes and are:

- Air separation
- Gasification (surface or underground)
- Gas cleaning/processing/blending
- Combustion/gas turbine
- Heat recovery steam generation
- Steam turbine

![Figure 5.2: Basic process diagram for IGCC-type plants](image-url)
An additional unit for carbon removal can be added to make a low Greenhouse emission configuration, either requiring simply a carbon dioxide removal unit after gas cleaning or also a shift reactor to convert carbon monoxide to carbon dioxide before the removal. With currently available technologies removal of 80 to 90% of the carbon dioxide in a gas stream is regarded as feasible, however it should be noted that the gas turbine must be suitable for use with high hydrogen content fuel gas. Most modern turbines are only suitable for use of fuel gas with up to 55% hydrogen, so processes that perform a shift reaction before carbon dioxide removal are largely hypothetical.

The differences between the technologies could be considered for process simulation as simply tuning of the IGCC process, however some plant items are likely to be significantly different in design and operation for the two processes. Some of the key changes when adapting an IGCC process to UCGCC are expected to be that UCG will have:

- No coal preparation plant
- No steam generation from the gasifier
- Higher hydrocarbons in the raw gas that need removal

On face value, the net effect of this appears to be a slightly lower parasitic power consumption in the plant and an increase in the proportion of power generated by the higher efficiency gas turbine, compared to the lower efficiency steam turbine. The key reason for this is that a well-designed UCG system allows longer residence time, so more of the energy of the coal should be extracted as chemical energy instead of heat, and this can be converted to electricity in a slightly more efficient manner. A by-product of the UCG process, however, is the production of tars that are not readily combustible in gas turbine plant and must be removed. The options for tar handling have not been fully examined but if the sulfur content is low they can be sold as oil refinery feed or they can be reformed by reaction with steam to produce more synthesis gas that can be combusted in the plant. Unfortunately, accurate prediction of the composition of the tars and the exact quantity formed is not possible without performing experiments on the coal and, therefore, the plant design required for tar processing is not possible. An estimate of tar generation was made as part of specifying the UCG product gas composition in this study, but the tar is simply removed in the gas cleaning process to minimise the risk of inaccuracy in the analysis.

5.3.1 Fuel gas specification

A conventional surface gasifier process using a Destec gasifier, described as Case 1 in NETL (2000), will be used as the base for the process simulation. One of the most important specifications in IGCC processes is the quality of the fuel gas that is fed to the gas turbine combustor. This gas should be essentially free of particulates and higher hydrocarbons, as these are likely to increase maintenance on the turbine. As the product of a high temperature gasification process, the raw Destec fuel gas is essentially free of higher hydrocarbons and has minimal methane, which is significantly different to the product gas from UCG. The methane is not a concern and non-condensable hydrocarbons, such as propane, are not of concern in minor quantities. The cleaning process in the NETL study involved quenching the raw gas in a wet scrubber before cold gas cleaning with sulfur and ammonia removal. The first stage of this should satisfactorily remove higher hydrocarbons from UCG product gas, as well as the relatively minor particulate loading. The fuel gas specification of major interest then becomes the composition going to the gas turbine combustor as clean gas.

Based on the past experience with UCG worldwide, it was decided that two case studies for the potential site in the Surat Basin would be considered to cover the likely range of UCG product gas. The first of these represents a moderately successful process operation that is line with past trials that functioned satisfactorily, denoted the “Good” case. The other case represents an operation with significant faults, such as the cavity having excessive water inflow and heat loss, denoted as the “Bad” case. The performance characteristics of these two cases were predicted using the modelling tools developed by CSIRO described in section 3.2 plus reference to experimental results from past trials, most notably the Rocky Mountain 1 trial. Gasifier product gas characteristics for the two UCG cases and the Destec case are summarised in Table 5.1. It should be noted that only major gas species have been included in the table and minor non-condensable hydrocarbons, such as propane and butane, are responsible for approximately 5% of the calorific value of the UCG sourced gas. The fundamental difference between
the cases is the lower calorific value of the clean gas from the Bad case arises from the higher energy losses during gasification. It is not intended that these cases represent the limits of performance of the site. In fact, the Good case was determined as a conservative estimate based on the apparent characteristics of the site and UCG experience on coal seams of similar suitability suggests that gas of significantly higher calorific value is possible.

Table 5.1: Characteristics of the clean fuel gas and preparation for IGCC case studies

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Units</th>
<th>Destec case</th>
<th>Good case</th>
<th>Bad case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen (95mol%) required</td>
<td>kg:m$^3$ clean gas</td>
<td>0.364</td>
<td>0.394</td>
<td>0.457</td>
</tr>
<tr>
<td>Coal consumed</td>
<td>kg:m$^3$ clean gas</td>
<td>0.478</td>
<td>0.446</td>
<td>0.425</td>
</tr>
<tr>
<td>Water used</td>
<td>kg:m$^3$ clean gas</td>
<td>0.377 (+0.59 steam)</td>
<td>0.352</td>
<td>0.436</td>
</tr>
<tr>
<td>Raw gas</td>
<td>m$^3$:m$^3$ clean gas</td>
<td>1.328</td>
<td>1.327</td>
<td>1.327</td>
</tr>
<tr>
<td>Condensate removed</td>
<td>litres:m$^3$ clean gas</td>
<td>Negligible</td>
<td>0.242</td>
<td>0.242</td>
</tr>
<tr>
<td>Particulates removed</td>
<td>mg:m$^3$ clean gas</td>
<td>Not available</td>
<td>6.36</td>
<td>6.36</td>
</tr>
<tr>
<td>Pressure</td>
<td>kPa</td>
<td>2344</td>
<td>2760</td>
<td>2760</td>
</tr>
<tr>
<td>Temperature</td>
<td>°C</td>
<td>46.67</td>
<td>45.00</td>
<td>45.00</td>
</tr>
<tr>
<td>Calorific value</td>
<td>MJ/m$^3$ (HHV, 25°C, 1atm)</td>
<td>10.25</td>
<td>11.45</td>
<td>10.22</td>
</tr>
<tr>
<td></td>
<td>MJ/kg (HHV, 25°C, 1atm)</td>
<td>13.12</td>
<td>11.91</td>
<td>10.55</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>Volume%</td>
<td>38.76</td>
<td>31.40</td>
<td>34.46</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>Volume%</td>
<td>8.49</td>
<td>28.80</td>
<td>32.17</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>Volume%</td>
<td>50.24</td>
<td>25.98</td>
<td>22.75</td>
</tr>
<tr>
<td>Methane</td>
<td>Volume%</td>
<td>0.10</td>
<td>10.54</td>
<td>7.20</td>
</tr>
<tr>
<td>Ethane</td>
<td>Volume%</td>
<td>0.00</td>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>Hydrogen sulfide</td>
<td>Volume%</td>
<td>0.01</td>
<td>0.01</td>
<td>0.19</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>Volume%</td>
<td>1.10</td>
<td>2.03</td>
<td>2.16</td>
</tr>
<tr>
<td>C:H ratio</td>
<td>Molar ratio, dry gas</td>
<td>0.755</td>
<td>0.610</td>
<td>0.621</td>
</tr>
</tbody>
</table>

A curious difference between the Destec and UCG fuel gases is evident in Table 5.1 on careful examination of the calorific value of the gases. Two sets of units are given and it is indicated that the calorific value of the Good UCG gas is higher than the Destec on a per volume basis, but lower on a per mass basis. This is a fundamental difference that has important ramifications in performance and the suitability of the gases for different processes. For example, gas turbine flow specifications are typically on a mass flow basis and this will mean that the mass flow of Destec gas required will be lower. In contrast, a reciprocating engine specification is in terms of volume flow and, therefore, the Good UCG gas would have the lower requirement. There is also a noticeable difference between the carbon to hydrogen ratios for the UCG and Destec gases. The UCG process generates lower carbon content gas because of the residual char left in the ground and the tars that are removed before combustion of the fuel gas.

5.3.2 IGCC process simulation

Prediction of Greenhouse emissions is heavily reliant on process simulation, as this allows representation of plant items in configurations that can give accurate estimation of the efficiency of electricity generation. The selected IGCC process is based around a coal slurry fed Destec surface gasifier with a Westinghouse W501G gas turbine set, Case 1 in NETL (2000). This is a fairly standard IGCC process using existing technologies, such as a fuel gas quench followed by cold gas cleaning and sulfur removal. A simulation of the process as specified in the literature was prepared in the HYSYS. Process simulation package and the performance of the process components set to match the published output. This allows that alternate configurations can be simulated using the same equipment performance characteristics, but with the key requirement that the feeds to the components be similar in essential characteristics to those in the published case study. Most importantly, the feed to the gas turbine system must match the specification with regard to temperature, pressure and mass flow rate. It was originally intended that the
IGCC process be adapted to represent the performance of an Australian coal, but it is not anticipated that there would be significant differences in the specification of the major equipment or process performance to the published case.

The same Destec IGCC process was used in Beath (2003), an earlier analysis of costs for UCG processes, and it should be noted that there are two significant differences between the assumptions used in that study and this continuation of it. The earlier study involved only a simplified process evaluation and it was taken from the process flowsheet in NETL (2000) that no steam was generated from the Destec gasifier. However, more detailed process analysis in the current work indicated that substantial steam is generated from non-specific heat sources in the process, most likely from fuel gas cooling at the gasifier exit but possibly including other heat sources. This current analysis allows for this difference to the UCG process, with a reduction of approximately 50MWe in steam turbine output for the UCG case. Also, the previous study assumed that the UCG product gas was similar to the Destec product gas in terms of performance in the gas turbine system with minor correction for changes in calorific value. This is not strictly correct, the differences in the composition of the gas lead to significant differences in the mixture of air, fuel gas and nitrogen required to achieve the correct combustor conditions for the gas turbine. This has been accounted for in the current study; however, advanced gas turbine modelling would be required to validate the predictions for the extremely high hydrogen content fuels that occur with high levels of carbon removal from the fuel gas and it is likely that this type of gas will be outside the operating specifications for the turbine set.

Three different process configurations are of relevance to this study. The first is of the standard IGCC type with adaptation simply to allow for the use of the different fuel gas compositions. The second is a configuration termed IGCC-CO2, which is a modification of the IGCC process that includes extra plant for the removal of 90% of the carbon dioxide present in the fuel gas. The third configuration is significantly more complex and incorporates two water-gas shift reactors (high and low temperature) before removal of 90% of the carbon dioxide, with this being termed the IGCC-Shift process. In last two cases adjustment to the gas temperature may be required to meet the specifications for the gas processing plant. In the simulations for these processes with different feed gases an attempt was made to keep the changes to the process at the minimum possible, while staying within the acceptable plant performance parameters. The major problem area with this is that the cases with carbon removal tend to elevate the hydrogen content in the fuel gas to levels that are likely to hinder the performance of the gas turbine system. Notes on the methods used for determining the size and costs of the carbon dioxide removal plant and shift reactors are given in Appendix B.

A summary of the power generation and consumption in each of the case studies is given in Table 5.2. All major power production and consumption plant items were considered in the process simulation excepting coal preparation, generator losses and auxiliary systems. Estimates for these were taken on a pro-rata basis as given in NETL (2000) and it can be seen in the table that these constitute a very minor part of the overall energy flows.
Table 5.2: Summary of IGCC configuration characteristics

<table>
<thead>
<tr>
<th>IGCC</th>
<th>Destec</th>
<th>Good UCG</th>
<th>Bad UCG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam turbine output, MWₜ</td>
<td>174.8</td>
<td>122.7</td>
<td>123.0</td>
</tr>
<tr>
<td>Gas turbine output, MWₜ</td>
<td>513.8</td>
<td>517.3</td>
<td>517.1</td>
</tr>
<tr>
<td>Compressor usage, MWₜ</td>
<td>237.1</td>
<td>241.4</td>
<td>250.3</td>
</tr>
<tr>
<td>Generator losses, MWₜ</td>
<td>6.5</td>
<td>5.8</td>
<td>5.8</td>
</tr>
<tr>
<td>Oxygen plant, MWₜ</td>
<td>26.0</td>
<td>26.3</td>
<td>34.4</td>
</tr>
<tr>
<td>Major pumps, MWₜ</td>
<td>2.0</td>
<td>2.1</td>
<td>2.1</td>
</tr>
<tr>
<td>Heating/Cooling, MWₜ</td>
<td>8.2</td>
<td>9.2</td>
<td>10.3</td>
</tr>
<tr>
<td>Auxiliary, MWₜ</td>
<td>8.2</td>
<td>5.6</td>
<td>5.6</td>
</tr>
<tr>
<td>CO₂ Shift &amp; Remove, MWₜ</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Net power output, MWₜ</td>
<td>400.6</td>
<td>349.7</td>
<td>331.5</td>
</tr>
<tr>
<td>CO₂ emissions, t/MWh</td>
<td>0.644</td>
<td>0.814</td>
<td>0.926</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>IGCC-CO₂</th>
<th>Destec</th>
<th>Good UCG</th>
<th>Bad UCG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam turbine output, MWₜ</td>
<td>173.9</td>
<td>119.0</td>
<td>119.9</td>
</tr>
<tr>
<td>Gas turbine output, MWₜ</td>
<td>515.8</td>
<td>523.3</td>
<td>524.6</td>
</tr>
<tr>
<td>Compressor usage, MWₜ</td>
<td>238.4</td>
<td>245.3</td>
<td>255.1</td>
</tr>
<tr>
<td>Generator losses, MWₜ</td>
<td>6.5</td>
<td>5.8</td>
<td>5.8</td>
</tr>
<tr>
<td>Oxygen plant, MWₜ</td>
<td>26.0</td>
<td>26.0</td>
<td>34.2</td>
</tr>
<tr>
<td>Major pumps, MWₜ</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Heating/Cooling, MWₜ</td>
<td>7.2</td>
<td>6.1</td>
<td>6.5</td>
</tr>
<tr>
<td>Auxiliary, MWₜ</td>
<td>8.2</td>
<td>5.6</td>
<td>5.6</td>
</tr>
<tr>
<td>CO₂ Shift &amp; Remove, MWₜ</td>
<td>15.0</td>
<td>8.7</td>
<td>11.4</td>
</tr>
<tr>
<td>Net power output, MWₜ</td>
<td>386.5</td>
<td>342.7</td>
<td>323.9</td>
</tr>
<tr>
<td>CO₂ emissions, t/MWh</td>
<td>0.580</td>
<td>0.511</td>
<td>0.521</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>IGCC-Shift</th>
<th>Destec</th>
<th>Good UCG</th>
<th>Bad UCG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam turbine output, MWₜ</td>
<td>64.6</td>
<td>73.6</td>
<td>77.4</td>
</tr>
<tr>
<td>Gas turbine output, MWₜ</td>
<td>546.7</td>
<td>537.7</td>
<td>538.6</td>
</tr>
<tr>
<td>Compressor usage, MWₜ</td>
<td>253.7</td>
<td>252.2</td>
<td>262.8</td>
</tr>
<tr>
<td>Generator losses, MWₜ</td>
<td>5.1</td>
<td>5.2</td>
<td>5.2</td>
</tr>
<tr>
<td>Oxygen plant, MWₜ</td>
<td>29.6</td>
<td>27.7</td>
<td>36.3</td>
</tr>
<tr>
<td>Major pumps, MWₜ</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
</tr>
<tr>
<td>Heating/Cooling, MWₜ</td>
<td>15.3</td>
<td>19.7</td>
<td>21.3</td>
</tr>
<tr>
<td>Auxiliary, MWₜ</td>
<td>7.8</td>
<td>5.3</td>
<td>5.4</td>
</tr>
<tr>
<td>CO₂ Shift &amp; Remove, MWₜ</td>
<td>32.4</td>
<td>26.6</td>
<td>29.0</td>
</tr>
<tr>
<td>Net power output, MWₜ</td>
<td>265.3</td>
<td>272.6</td>
<td>253.8</td>
</tr>
<tr>
<td>CO₂ emissions, t/MWh</td>
<td>0.149</td>
<td>0.328</td>
<td>0.338</td>
</tr>
</tbody>
</table>

Some simple observations can be made based on the figures given in the table. Starting with the conventional IGCC process, the only major difference in power output between the cases arises because of the lack of heat recovery from the gasifier and product gas from UCG, represented as an approximately 50MWe reduction in steam turbine output from the Destec case. The Bad UCG case also has a small increase in oxygen plant consumption due to the high oxygen demand assumed for the case. The other significant difference between the cases is the higher Greenhouse gas emission rate for the two UCG cases. This is a relatively unexpected result that contrasts markedly with previously published results and the lower carbon to hydrogen ratio of the UCG fuel gases. It occurs due to the combination of the lower calorific value per mass of gas requiring more fuel gas to be used and the combustor product gas containing a lower carbon dioxide concentration due to lower carbon content of the gas. This has an impact on the gas turbine operating characteristics, due to the lower density of the combusted product gas. It appears unlikely that the previously published results for oxygen-blown UCG power systems considered gas turbine operation to this level of simulation. The air-blown UCG study of CISS (2001) and the supporting paper by Blinderman & Anderson (2003) suggests that a detailed analysis of gas turbine performance was performed and actually indicated an improvement in gas turbine performance,
but the air-blown product gas is substantially different to that of an oxygen-blown system. In general, the poor gas turbine performance for an oxygen-blown UCG system is indicative of problems that occur when using low carbon fuels with gas turbines and is currently being addressed in turbine design changes to enable more efficient use of high-hydrogen fuels. The impact of this on the UCG process is to suggest that air-blown operations would be preferable for power generation, if carbon dioxide removal is not intended. The use of oxygen in surface gasifiers is typically intended to reduce the size of the gasifier in order to reduce the capital cost, which is a minor concern in UCG plant design. The product fuel gas is diluted before combustion, so the use of oxygen is not essential if an adequate gas quality can be achieved with air. In this study, the reason for the selection of oxygen was to allow consideration of the impact of carbon dioxide removal on the processes, and it is likely that an air-blown or an oxygen-enriched UCG process would be preferable as a simple UCG for electricity process.

The addition of carbon dioxide removal plant has a significantly higher impact on carbon dioxide emissions for the UCG based plants due to the higher carbon dioxide loading of the product gases. This means that a substantial portion of the carbon in the gas can be removed without a shift reactor and the Greenhouse emissions drop to comparable levels to some natural gas fired power plants for all cases considered. By adding a shift reactor, the carbon dioxide emissions from the Destec based plant can be reduced to extremely low values, but the UCG cases are not affected as significantly due to the methane in the fuel gas not being affected by the shift. The Greenhouse gas emissions from the UCG cases are still reduced below that of good natural gas combined cycle plants using low carbon dioxide natural gas supplies, but the Destec case is substantially lower. There is a major issue with the shift and removal processes as simulated, namely that it is unlikely that the process can be configured to suit any currently available gas turbine set. It is a subject of current research to improve the ability of gas turbines and combustors to handle high hydrogen content gases, and there is as yet no operating experience to prove the longevity of large turbines on this type of gas.

5.3.3 Process costs

The other key issue typically related to Greenhouse emissions from power plants is the cost of reducing the emissions. In Table 5.3 a summary of the capital and operating costs for the different plant configurations is given, as estimated from the data in NETL (2000), with supplementary input for UCG costs as described in Beath (2003) and carbon dioxide removal costs as estimated for this report. The core plant items have been sized and costed to a feasibility analysis standard, but auxiliary plant and many of the operating costs have been simply carried over as constant cost items from the NETL (2000) figures for all processes. Where necessary, costs have been converted from US currency using the method described in Graham et al. (2003), namely that an estimate of the portion of the equipment that must be sourced at international prices is subject to standard currency conversion while the equipment that can be sourced locally is costed using the typical ratio of US to Australian costs for power generation plant.

The capital cost of the basic IGCC processes is considerably lower for the UCG-based plants, due in most part to omission of the surface coal gasifier and associated coal preparation plant in favour of an array of drilled wells and piping. This is offset to some degree by a reduced power output resulting from differences in gas turbine performance and reduced steam generation for the UCG cases, resulting in less difference in the capital cost per unit of power exported than may have been expected. Operating costs are also lower for the UCG processes, mainly through cheaper access to coal through drilling and payment of royalties (7% of nominal value of the coal in Queensland), rather than commercial purchase of the coal. The overall impact of this on electricity cost is estimated by the levelised cost for the 10th year of plant operation, which indicates a substantially lower cost for the Good UCG process. This levelised cost method was developed by the Electric Power Research Institute (EPRI) to account for the interaction of capital, operating and fuel costs on the overall economics of a plant.

There are a number of methods for analysing the financial impact of Greenhouse gas emission reductions on electricity costs, but the trends are fairly evident. Without any attempt being made to reduce Greenhouse emissions the large scale UCG plants appear financially competitive with conventional power plant in Australia, even if performance of the UCG process is below optimum. In the oxygen-blown UCG cases considered, it appears likely that this will be with only a small Greenhouse emission benefit over
conventional coal fired boiler plant. The Destec IGCC process has a substantially higher cost, but does provide a significant Greenhouse gas improvement. The cost of electricity increases with carbon dioxide removal plant, but the UCG cases may still be reasonably competitive with conventional plant and there is a substantial reduction in Greenhouse emissions. The addition of this plant has reduced the impact of UCG operational performance on the overall plant emissions, so there is less difference between the two UCG cases. The removal of the carbon dioxide improves the energy density of the fuel gas and has had such a dramatic impact on the Bad UCG case that it is indicated that electricity should be cheaper to produce with carbon dioxide removal. Addition of shift plant to increase the amount of carbon that can be removed from the fuel has a large impact on the cost of electricity. This is particularly the case for the Destec system, but it should be noted that there is a major reduction in Greenhouse gases with this case. The UCG cases have lower cost, but there is again a substantial difference between the costs for the two cases that indicates that the UCG plant must be well run to be effective.

5.3.4 Other process issues
While not directly related to this area of the study, a particular item of concern in the region of the site is the cooling requirement for each of the processes. The recently constructed Millmerran power station, in the vicinity of the selected UCG site, uses dry cooling rather than the more conventional water cooling due to restricted access to water in the region. This has an impact on the operating efficiency of the steam cycle in the power plant, so reduces plant output. The plant options with a shift reactor in this study have large cooling requirements, so may not be feasible in this region.

Process water usage is similarly a concern with regard to the viability of the processes, mostly if the Destec gasifier was to be used near the selected location. This is a coal slurry fed gasifier with direct steam heating of the slurry, so a well designed water recovery system must be used to prevent excessive losses of water. The UCG process is less of an issue in the region as it will use groundwater and be a net producer of water at the surface. A similar quantity of water to the Destec system will be recovered in the gas cleaning plant, but surplus water is likely to be available for cooling, re-injection into the ground (if required) or release for agricultural purposes after treatment.
Table 5.3: Summary of costs associated with the IGCC configurations

<table>
<thead>
<tr>
<th>IGCC</th>
<th>Destec</th>
<th>Good UCG</th>
<th>Bad UCG</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CAPITAL COSTS (A$million)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air separation</td>
<td>46.622</td>
<td>47.153</td>
<td>61.723</td>
</tr>
<tr>
<td>Gasification system</td>
<td>111.998</td>
<td>2.907</td>
<td>2.750</td>
</tr>
<tr>
<td>Gas processing</td>
<td>26.435</td>
<td>32.180</td>
<td>36.649</td>
</tr>
<tr>
<td>Gas turbine system</td>
<td>77.337</td>
<td>77.337</td>
<td>77.337</td>
</tr>
<tr>
<td>Steam plant system</td>
<td>48.810</td>
<td>42.489</td>
<td>42.979</td>
</tr>
<tr>
<td>Other plant</td>
<td>69.402</td>
<td>69.402</td>
<td>69.402</td>
</tr>
<tr>
<td>Total Capital (including on-costs)</td>
<td>568.287</td>
<td>405.334</td>
<td>434.258</td>
</tr>
<tr>
<td>Capital A$/kW</td>
<td>1419</td>
<td>1159</td>
<td>1310</td>
</tr>
<tr>
<td><strong>OPERATING (A$million/yr)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coal</td>
<td>28.482</td>
<td>1.994</td>
<td>1.976</td>
</tr>
<tr>
<td>Drilling</td>
<td>0.000</td>
<td>2.471</td>
<td>2.338</td>
</tr>
<tr>
<td>Labour &amp; Maintenance</td>
<td>17.220</td>
<td>17.220</td>
<td>17.220</td>
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<tr>
<td>Other</td>
<td>2.707</td>
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<td>1.760</td>
</tr>
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<td>Credits (Sulfur &amp; Tars)</td>
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</tr>
<tr>
<td>Total Operating (Net)</td>
<td>48.409</td>
<td>23.405</td>
<td>23.293</td>
</tr>
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<td>Levelised electricity cost (10\textsuperscript{th} year, A$/MWh)</td>
<td>43.90</td>
<td>28.92</td>
<td>44.24</td>
</tr>
<tr>
<td><strong>IGCC-CO2</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td><strong>CAPITAL COSTS (A$million)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air separation</td>
<td>46.615</td>
<td>46.662</td>
<td>61.242</td>
</tr>
<tr>
<td>Gasification system</td>
<td>111.809</td>
<td>2.886</td>
<td>2.730</td>
</tr>
<tr>
<td>Gas processing</td>
<td>92.171</td>
<td>52.368</td>
<td>56.860</td>
</tr>
<tr>
<td>Gas turbine system</td>
<td>77.337</td>
<td>77.337</td>
<td>77.337</td>
</tr>
<tr>
<td>Steam plant system</td>
<td>48.418</td>
<td>41.437</td>
<td>41.468</td>
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<td>Other plant</td>
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<td>69.402</td>
<td>69.402</td>
</tr>
<tr>
<td>Total Capital (including on-costs)</td>
<td>665.560</td>
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<tr>
<td>Capital US$/kW</td>
<td>1722</td>
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<td>1424</td>
</tr>
<tr>
<td><strong>OPERATING (A$million/yr)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coal</td>
<td>28.434</td>
<td>1.979</td>
<td>1.856</td>
</tr>
<tr>
<td>Drilling</td>
<td>0.000</td>
<td>2.453</td>
<td>2.321</td>
</tr>
<tr>
<td>Labour &amp; Maintenance</td>
<td>18.295</td>
<td>17.660</td>
<td>17.662</td>
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<tr>
<td>Other</td>
<td>2.705</td>
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<td>Credits (Sulfur &amp; Tars)</td>
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<td>0.000</td>
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<tr>
<td>Total Operating (Net)</td>
<td>49.434</td>
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<td>23.594</td>
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<td>Levelised electricity cost (10\textsuperscript{th} year, A$/MWh)</td>
<td>50.86</td>
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<td><strong>IGCC-Shift</strong></td>
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</tr>
<tr>
<td><strong>CAPITAL COSTS (A$million)</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Air separation</td>
<td>53.072</td>
<td>49.730</td>
<td>65.179</td>
</tr>
<tr>
<td>Gasification system</td>
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<td>Gas processing</td>
<td>87.713</td>
<td>84.919</td>
<td>90.960</td>
</tr>
<tr>
<td>Gas turbine system</td>
<td>77.337</td>
<td>77.337</td>
<td>77.337</td>
</tr>
<tr>
<td>Steam plant system</td>
<td>34.911</td>
<td>35.708</td>
<td>36.269</td>
</tr>
<tr>
<td>Other plant</td>
<td>69.402</td>
<td>69.402</td>
<td>69.402</td>
</tr>
<tr>
<td>Total Capital (including on-costs)</td>
<td>671.670</td>
<td>478.042</td>
<td>510.720</td>
</tr>
<tr>
<td>Capital US$/kW</td>
<td>2532</td>
<td>1754</td>
<td>2012</td>
</tr>
<tr>
<td><strong>OPERATING (A$million/yr)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coal</td>
<td>32.401</td>
<td>2.089</td>
<td>1.852</td>
</tr>
<tr>
<td>Drilling</td>
<td>0.000</td>
<td>2.608</td>
<td>2.467</td>
</tr>
<tr>
<td>Labour &amp; Maintenance</td>
<td>18.181</td>
<td>18.087</td>
<td>18.108</td>
</tr>
<tr>
<td>Other</td>
<td>2.883</td>
<td>1.736</td>
<td>1.776</td>
</tr>
<tr>
<td>Credits (Sulfur &amp; Tars)</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Total Operating (Net)</td>
<td>53.465</td>
<td>24.519</td>
<td>24.203</td>
</tr>
<tr>
<td>Levelised electricity cost (10\textsuperscript{th} year, A$/MWh)</td>
<td>76.48</td>
<td>46.85</td>
<td>52.72</td>
</tr>
</tbody>
</table>
5.4 Summary

A detailed analysis of the Greenhouse emissions and costs for electricity generation was performed considering two UCG cases, one using conservative estimates of performance at the selected site and the other an artificially degraded performance as an indicator of sensitivity to the UCG operation, and an IGCC case based on a current technology surface gasifier plant. The findings of this study are summarised in Figure 5.3, along with indicative results for Greenhouse emissions from conventional coal fired power plant and combined cycle natural gas plant sourced from CISS (2001) and air-blown UCG data based on the Chinchilla trial from Blinderman and Anderson (2003). It should be noted that there were differences between the methods used in these studies and those used in this study, so the other data should be taken as approximate in this context. The natural gas case referenced is a life cycle analysis where the natural gas contained 30% carbon dioxide that was vented in processing. In Figure 5.4, the systems are compared on a basis of the cost of electricity produced, with the cost indications for conventional coal fired plant and combined cycle natural gas plant sourced from Williams (2002) and the air-blown UCG data from Blinderman and Anderson (2003). Again, the costs are not directly comparable with those in the current study. In combination, the Greenhouse emission and cost data show that the Destec systems perform well in terms of Greenhouse emissions, but the production cost of electricity is high, in particular for the carbon dioxide removal options. In the basic IGCC configuration, the UCG systems are not particularly attractive and compare poorly with the air-blown UCG figures based on the Chinchilla trial. However, with the simple carbon dioxide removal system there are significant benefits in terms of Greenhouse gas reductions and electricity is produced at a cost comparable to conventional coal fired power plant. The carbon dioxide removal plant also reduces the sensitivity of the plant emissions and cost to the UCG operational performance. In all cases the use of a shift reactor before carbon dioxide removal results in a significant increase in electricity production cost that appears difficult to justify in a competitive electricity supply industry without some form of subsidy.

This study highlights some significant issues regarding the behaviour of existing gas turbine systems. The UCG sourced fuel gas appears less suitable for existing gas turbine systems than surface gasifier fuel gas and is likely to have higher Greenhouse emissions in standard IGCC systems, despite having lower carbon content, due to poor performance in the gas turbine system. This exposes a problem with the current trends in clean coal technology using gas turbines with low carbon fuels and is an area of research for gas turbine specialists. If carbon dioxide removal is added to the process, the fuel gas changes dramatically for UCG sourced gas and the higher methane content gas performs well in the gas turbine system, resulting in substantial Greenhouse gas emission reductions. The use of a shift reactor to convert carbon monoxide to carbon dioxide prior to the removal process has a relatively minor impact on the UCG cases, because the methane is not removed, but causes a major reduction in the surface IGCC plant Greenhouse emissions due to the high carbon monoxide content of the raw fuel gas. However, this process option is problematic, as none of the currently available gas turbine systems are suitable to use the fuel gas resulting from this processing due to the high hydrogen content. This is a significant issue in the development of clean coal technologies in general.
Figure 5.3: Comparison of Greenhouse emissions for generation options

Figure 5.4: Comparison of electricity costs for generation options
6 GROUNDWATER AND SUBSIDENCE IMPACTS

6.1 Groundwater issues

This section describes the results of a preliminary investigation into the possible adverse impact of UCG on groundwater availability and quality, the likelihood of operational problems due to excessive groundwater inflow into the operating gasification cavities and the surface subsidence to be expected above the UCG panels. For this investigation, numerical models were constructed (based on possible operations in the eastern Surat Basin, as described in Section 4) to predict:

- flow rates of groundwater into the gasification cavities during operation and shutdown of UCG;
- changes in surrounding static water levels, flow velocities and paths during operation and the recovery of water levels within the UCG panel and in the surrounding aquifers after operation;
- flow of groundwater and transport of contaminants from within the UCG panel;
- subsidence on the surface due to UCG; and
- the sensitivity of predictions to some uncertain parameters.

6.2 Methods used to estimate impact of UCG on groundwater and subsidence

It is not currently computationally feasible to use a single model to simulate the mechanics and hydrology at a regional scale with sufficient resolution to capture the required detail of the gasification process. For this reason, two different types of model were used: one for issues that are local to the UCG panel (rock mechanics associated with the creation of cavities, flow into the gasification cavities and hydrology changes in the immediate vicinity of the panel) and one for regional issues (broader area changes in hydrology and containment of contaminants). These models are described in Sections 6.2.1 and 6.2.2 respectively. Both models use a base case scenario that is described in Section 4.

The geological strata included in the models (from the surface down) are simplified from those obtained by Sliwa and Fraser (2004) and are listed in Table 6.1. These are the only strata included in the local or regional models. Although there are strata above the Westbourne formation for parts of the regional model, groundwater in these strata is unlikely to impact on the UCG operations in any significant way as these strata are remote from the site and there is no mechanism to generate a high permeability path to the UCG site. For the local model, the top surface consists of Westbourne formation rocks. For both models, leakage between the targeted coal seam and aquifers below the Walloon Coal Measures is unlikely to be significant and these strata may be ignored.

The stratigraphy is known to be quite variable in this area (Sliwa and Fraser 2004) and the details of the strata thicknesses may differ significantly from Table 6.1 at other locations.

Table 6.1: The geological formations included in the base case models

<table>
<thead>
<tr>
<th>Formation name</th>
<th>Thickness at well 50207</th>
<th>Common rock types</th>
<th>Estimated permeability measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Westbourne formation</td>
<td>287m</td>
<td>Siltstone, mudstone, fine quartzose to labile sandstone</td>
<td>low</td>
</tr>
<tr>
<td>Springbok sandstone</td>
<td>33m</td>
<td>Sandstone, siltstone, mudstone and some coal</td>
<td>high</td>
</tr>
<tr>
<td>Upper Walloon coal measures</td>
<td>65m</td>
<td>Lithic sandstone, siltstone, mudstone, coal</td>
<td>low</td>
</tr>
<tr>
<td>385 and 390 coal measures</td>
<td>10m</td>
<td>Coal</td>
<td>medium to high</td>
</tr>
<tr>
<td>Lower Walloon coal measures</td>
<td>165m</td>
<td>Lithic sandstone, siltstone, mudstone, coal</td>
<td>low</td>
</tr>
</tbody>
</table>

6.2.1 The local model

The local model is of a rectangular area that is bounded in plan 3km from the UCG panels, as shown in Figure 6.1. The seam and interfaces between the strata in Table 6.1 are assumed to dip at 2° in the
direction shown in the figure (based on data provided by Sliwa and Fraser (2004)). The top surface and base of the model are horizontal. The total depth of the model is 560m and the coal targeted for gasification is a seam 10m thick between 385m and 395m depth (described as 385 and 390 coal measures in Table 6.1).

A gravitational initial vertical stress state was assumed with horizontal stresses 0.8 times vertical in the gasification seam and 1.5 times vertical in other strata. Roller (i.e. no displacement perpendicular to the boundary face) boundary conditions were imposed on the vertical faces and the base of the model.

**Figure 6.1: Plan view of the local model showing cavity layout and model outer boundary**

This region is simulated for 2.3 years while the gasification is in operation, followed by 2 years while the cavities are flushed to clean most of the potential contaminants. For consistency with the regional model, the gasification is assumed to take place in ten steps of 0.23 years. The gasification is assumed to occur simultaneously in each of the three cavities and, at the start of each step, a section 180m wide by 600m long by 10m high of coal is removed from each cavity in the model. This is followed by an initial mechanical equilibration, which occurs instantaneously in the model, followed by 0.23 years of coupled flow/mechanical simulation to predict the water flow into the cavities and the hydrological changes that occur during the gasification.

During the gasification stage, the gas pressure in the cavity is assumed to be slightly below the water pore pressure around the cavity (3MPa compared with the pre-gasification pore water pressure of 3.4MPa at the highest point of the final cavities). This is to ensure that there is no water flow out of the cavities (all flow will be towards the lower pressure cavities) and consequently no opportunity for contaminant escape.
during the gasification. For the shutdown stage, the gas pressure in the cavities is assumed to reduce to atmospheric pressure and water is assumed to be pumped out as it enters the cavity. The amount of water predicted to flow into each cavity as time progressed was noted. In addition, the predictions of rock displacements, stresses, pore pressure, saturation and permeability changes due to rock failure at the end of each of the ten steps and at the end of the shutdown stage was recorded.

There was little information about the water table level at the selected location. It was assumed in the base case that the water table level was 20m below the surface, as is typical of some other locations in the area (Sliwa and Fraser (2004)). Initial pore pressures to give equilibrium with gravity were assumed. Constant pressure boundary conditions were imposed on the vertical faces of the model and the base of the model used a no-flow boundary condition. No recharge or water extraction was assumed in the local model.

The computer code used in the model is COSFLOW and is described in Section 4. The important material parameters for the formations represented in the model are listed in Table 6.2. The Westbourne formation is split into two, with no water in the top 20m. The Upper Walloon Coal Measures are split into three, the top and bottom being sandstone and the middle being siltstone. The Cosserat model simulates a bedded material (with bedding thickness and cohesion listed in the table) for all strata apart from the coal seam, which is modelled as a conventional Mohr Coulomb material.

Table 6.2: Rock strength and initial permeability values used in the local model

<table>
<thead>
<tr>
<th>Formation</th>
<th>Depth range at well 50207 (m)</th>
<th>Young’s modulus (GPa)</th>
<th>Rock UCS (MPa)</th>
<th>Rock tension cutoff (MPa)</th>
<th>Bedding spacing (m)</th>
<th>Joint cohesion (MPa)</th>
<th>Horizontal permeability ($\times 10^{-15}$ m$^2$)</th>
<th>Vertical permeability ($\times 10^{-15}$ m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Westbourne formation</td>
<td>0-20</td>
<td>5.</td>
<td>9.6</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>No water</td>
<td>No water</td>
</tr>
<tr>
<td>Westbourne formation</td>
<td>20-287</td>
<td>5.</td>
<td>9.6</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>11.6</td>
<td>1.2</td>
</tr>
<tr>
<td>Springbok sandstone</td>
<td>287-320</td>
<td>15.</td>
<td>28.8</td>
<td>1.5</td>
<td>5.</td>
<td>0.5</td>
<td>1160</td>
<td>116</td>
</tr>
<tr>
<td>Upper Walloon coal measures</td>
<td>320-338</td>
<td>15.</td>
<td>28.8</td>
<td>1.5</td>
<td>5.</td>
<td>0.5</td>
<td>11.6</td>
<td>1.2</td>
</tr>
<tr>
<td>Upper Walloon coal measures</td>
<td>338-380</td>
<td>10.</td>
<td>19.2</td>
<td>1.</td>
<td>0.5</td>
<td>0.5</td>
<td>11.6</td>
<td>1.2</td>
</tr>
<tr>
<td>Upper Walloon coal measures</td>
<td>380-385</td>
<td>15.</td>
<td>28.8</td>
<td>1.5</td>
<td>5.</td>
<td>0.5</td>
<td>11.6</td>
<td>1.2</td>
</tr>
<tr>
<td>385 and 390 coal measures</td>
<td>385-395</td>
<td>3.5</td>
<td>9.6</td>
<td>0.5</td>
<td>N/A</td>
<td>Large</td>
<td>46.4</td>
<td>4.6</td>
</tr>
<tr>
<td>Lower Walloon coal measures</td>
<td>395-560</td>
<td>5.</td>
<td>9.6</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>11.6</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Many of the assumptions described in the preceding paragraphs are uncertain and some of these were varied and the model rerun to assess the sensitivity of the predictions to these changes. The variations are listed in Table 6.3.
Table 6.3: Local model variations

<table>
<thead>
<tr>
<th>Case number</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Base case</td>
</tr>
<tr>
<td>2</td>
<td>Base case with cavity gas pressure reduced to 2.5MPa (instead of 3MPa)</td>
</tr>
<tr>
<td>3</td>
<td>Case 2 with the water table level 70m below the surface (increased from 20m)</td>
</tr>
<tr>
<td>4</td>
<td>Base case with all rock permeabilities reduced by a factor of 10</td>
</tr>
<tr>
<td>5</td>
<td>Case 2 with all rock permeabilities reduced by a factor of 10</td>
</tr>
<tr>
<td>6</td>
<td>Base case with gasifications in only the outer two cavities</td>
</tr>
<tr>
<td>7</td>
<td>Base case with gasification only in the inner cavity</td>
</tr>
<tr>
<td>8</td>
<td>Base case with alternative cavity layout design</td>
</tr>
</tbody>
</table>

In addition to the base case design, an alternative design (case 8), based on Davis (1999), was modelled. This design has ten smaller cavities, each of length 200m and width 30m, with 15m pillars, as shown in plan in Figure 6.2. The gasification is again simulated in ten equal steps, with all cavities running concurrently. Because of their smaller size, it is expected that these panels will not cave during the gasification. The same geological structure and material properties are assumed as for the base case.

![Figure 6.2: Plan view of alternate cavity layout (case 8)](image)

6.2.2 The regional model

The regional model simulates that part of the eastern Surat Basin shown in plan in Figure 6.3. The model consists of eight layers and includes the formations listed in Table 6.1. The Westbourne formation, Springbok sandstone and Upper Walloon Coal Measures are each split into two layers to allow for variation with depth in permeability changes from rock fracture. The 385 and 390 Coal Seam and the Lower Walloon Coal Measures are each allocated one layer. Boundaries between layers are based on horizon picks for the top of the various layers from borehole and other data described in Sliwa and Fraser (2004). The picks were interpolated over the study region, with some corrections made to account for intersections of interpolated layer boundaries. The eight layers of the model are shown in Figure 6.4.
Figure 6.3: Plan of East Surat Basin showing the extent of the regional model (white)

Figure 6.4: The stratigraphy in the regional model
A model grid was created, oriented with the y axis at 30° east of north, to be aligned with the direction of cavity creation. The grid spacing is 600m, reducing to 60m in the immediate vicinity of the cavities. This resulted in a model with approximately 1.2 million cells of which about one third are active (within the plan boundary shown in Figure 6.3).

Important parameters for the flow model are the permeabilities in the different layers, the water recharge and extraction rates. Only qualitative measures of permeability listed in Table 6.1 and based on stratigraphic and borehole data held by NRM&E were available. Groundwater recharge has been estimated by Kellet et al (2003) to total 19000m$^3$/day (or 4mm/year over the exposed area) for aquifers in the Springbok Sandstone with no significant natural discharge noted in the study area. It was initially assumed that recharge in the Westbourne Formation and Upper Walloon Coal Measures was 1mm/day. Groundwater usage data from the WERD database of NRM&E was analysed and 130 bores were identified within the Walloon Coal Measures, none in the Springbok and 3 in the Westbourne Formation within the study area.

The first task was to calibrate a steady-state regional model against available pore pressure measurements from NRM&E’s Ground Water Data Base. The parameters varied in the calibration were the permeabilities in the eight layers and the water recharge rates. The best fit was obtained with recharge rates shown in Figure 6.5 and permeabilities shown in Table 6.4. Notice that there are differences between the assumed permeabilities for the local model and those values, calibrated over the entire regional area, for the regional model.

![Figure 6.5: Calibrated recharge distribution (m/day) for the regional model](image)
### Table 6.4: Calibrated permeability distribution for the regional model

<table>
<thead>
<tr>
<th>Layer Number</th>
<th>Description</th>
<th>Horizontal Permeability ($\times 10^{-15}$ m$^2$)</th>
<th>Vertical Permeability ($\times 10^{-15}$ m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>upper Westbourne Formation</td>
<td>58.</td>
<td>5.8</td>
</tr>
<tr>
<td>2</td>
<td>lower Westbourne Formation</td>
<td>58.</td>
<td>5.8</td>
</tr>
<tr>
<td>3</td>
<td>upper Springbok Formation</td>
<td>4640.</td>
<td>464.</td>
</tr>
<tr>
<td>4</td>
<td>lower Springbok Formation</td>
<td>4640.</td>
<td>580.</td>
</tr>
<tr>
<td>5</td>
<td>upper upper Walloon Coal Measures</td>
<td>58.</td>
<td>5.8</td>
</tr>
<tr>
<td>6</td>
<td>lower upper Walloon Coal Measures</td>
<td>58.</td>
<td>5.8</td>
</tr>
<tr>
<td>7</td>
<td>390 Coal Seam</td>
<td>116.</td>
<td>116.</td>
</tr>
<tr>
<td>8</td>
<td>lower Walloon Coal Measures</td>
<td>116.</td>
<td>1.16</td>
</tr>
</tbody>
</table>

The next task was to simulate groundwater flow in the gasification, shutdown and post-shutdown stages. Each of the three 180m×600m cavities is represented by 3×10 cells with a 60m pillar between cavities of width one cell. Gasification is modelled to occur in ten equal steps of 0.23 years. For each step, three additional cells in each cavity are given fixed heads (333m above that at the base of the coal seam) that correspond to the gas pore pressure assumed for the cavity (3.25MPa). In addition, the permeability in the cells above the gasification cavities are modified to the values predicted by the local model on the basis of its rock fracture estimates. The shutdown stage (2 years) was modelled by setting the heads in the final row of cells to 0.3m above the base of the coal seam, to simulate constant drainage of the cavities, with very high permeability within the cavities. The post-shutdown stage was modelled by setting all the cavity cells to normal and water levels were allowed to recover for 1000 years.

The final task was to simulate contaminant transport in the 1000 year post-shutdown phase. Two types of contaminant were considered in two different models: salt and benzene. The initial salt concentration throughout the study area was assumed to be 1000mg/litre (no data were available) and the last row of cells in each cavity was set with an initial concentration of 10000mg/litre of salt (to simulate an ineffective cleanup with 108000m$^3$ of saline water remaining in each of the three cavities at the completion of the shutdown stage). The initial benzene concentration throughout the study area was assumed to be zero except in the UCG cavities, which were set as constant concentration cells at 0.01mg/litre to simulate the effect of an ineffective cleanup where a dense nonaqueous-phase liquid (DNAPL) such as tar or condensate remained within the cavities and acted as a long-term benzene source.

### 6.3 Summary of findings

This sub-section presents a summary of the findings from the local and regional models.

#### 6.3.1 Water inflow into cavity during gasification and cleanup from the local model

The estimated water inflow rate for the three cavities in the base case local model during the gasification period is shown in Figure 6.6. These flow rates are averages over each of the ten steps and measured as the amount of water flowing into the cavity for each tonne of coal gasified. The numerical values and flow rates in other units (litres/sec and m$^3$/year) are listed in Table 6.5.
The estimated flows into the two outer cavities are equal from the symmetry of the layout and assumed strata models. The estimated flow into the inner cavity is less than that into the outer cavities because the available water for the inner cavity is reduced by flow into the outer cavities. The flow rates increase as the size of the cavity grows as the surface area of cavity increases and thus more water (if available) can enter the cavity. The flow rates increase almost linearly for the first four stages but with a steeper slope for the final six stages because the model predicts significant fracturing up into the Springbok formation with consequent permeability increases at about the fifth stage.
The predicted flow rates during the gasification stage (maximum of 0.68 m$^3$/tonne of coal) are somewhat less than those expected to create problems with the efficiency of the gasification and should be able to be handled easily.

The average inflow rates for the outer cavities and inner cavity during the clean-up stage are predicted to be approximately 70 litres/sec and 61 litres/sec for the outer and inner cavities respectively. This rate is much higher than that during the gasification stage (maximum of 9.8 and 7.4 litres/sec respectively), because there is no longer an internal gas pressure in the cavity and the pressure difference between the pore water and the cavity boundary, which drives the flow, is much greater.

The predicted effect of lowering the cavity pressure from 3MPa to 2.5MPa (case 2) can be seen in Figure 6.7. The increased pressure gradient between the pore water and the cavity drives more water into the cavity. The predicted maximum water flows are 1.05 m$^3$/tonne of coal and 0.85 m$^3$/tonne of coal for the outer and inner cavities respectively, which represents a 67% and 77% increase in flow respectively, compared with the base case.

The permeability of the intact rock has been estimated, but there is some uncertainty in these estimates. The impact of a reduction in all intact rock permeabilities by a factor of 10 (case 4 with 3MPa cavity pressure and case 5 with 2.5MPa cavity pressure) can be seen in Figure 6.8. Predicted water flow is reduced by a factor of about 5. If actual rock permeabilities are greater than those estimated, there will be increased water flow into the cavities.
No firm design of the cavities has yet been made and the remaining cases investigated the impact of different designs. Figure 6.9 compares the predicted water flows of the base case with cases where only the two outer cavities are gasified (case 6) and only a single (inner) cavity is gasified (case 7). With only one or two cavities instead of three, more water is available for each cavity and the inflow is greater.
Figure 6.9: Comparison of water inflow prediction for cases 1, 6 and 7

A different design (case 8) is considered, where 10 cavities 30m by 200m are gasified simultaneously. Figure 6.10 shows the predicted water flow into each of the cavities. Again symmetry implies that the flow into a cavity to the left of the centre line will be the same as the flow into the corresponding cavity to the right of the centre line. The total flows into the smaller cavities are much less than for the base case, but the flow per tonne of coal mined is greater for the outer cavity, but less for the inner cavities. This design has a greater cavity surface area to volume ratio than for the base case with consequent greater potential for water inflow (which will depend on surface area) per tonne of coal (which will be proportional to the cavity volume). However, because there is reduced failure in the roof (see Section 6.3.4), the roof permeability is less than for the base case design.
6.3.2 Effect on water table, groundwater levels in surrounding aquifers, groundwater flow rates and flow paths during gasification, cleanup and beyond

Figure 6.11 shows the predicted water table height at the end of the gasification (stage 10) for the base case local model (the blue surface near the top of the half-model). At the UCG site, the water table is predicted to lower by approximately 17m. The local model only extends 3km in each direction from the UCG site and may not give a sufficient representation of the extent of lowering of the water table throughout the region. The figure also shows the isosurfaces corresponding to pore pressures of 2MPa and 4MPa (the green and yellow surfaces respectively). These isosurfaces are lowered by a maximum of 23m and 55m respectively at the UCG site (which corresponds to a reduction in pore pressure of about 0.2MPa and 0.5MPa respectively at these depths, or a bit over 10%). The UCG activity has a greater impact on pore pressure isosurfaces that are closer to the cavities and replenishment of water below the coal seam is slower because there are only low permeability connections to aquifers.

At the end of the cleanup stage (where all water entering the cavities is assumed to be pumped out immediately), the water table is predicted to lower by 80m.
The extent of the drawdown can be estimated from the regional model. Water levels gradually declined within the immediate area of the UCG cavities, as the proposed constant head was below the level in the surrounding aquifer. This maintained capture of any contaminated groundwater during the operational phase of the project. The piezometric surface after gasification is shown in Figure 6.12 and the drawdown (exceeding 0.5 m) shown in Figure 6.13, indicating an area of drawdown exceeding 0.5 m extending approximately 10 km to northwest-southwest-southeast and 5 km to the northeast. The 0.5m threshold used here would be barely detectable if at all (there is insufficient data on water levels to estimate likely natural fluctuations in water level). During the cleanup stage, water levels decline more (Figure 6.14) and the area of drawdown increased significantly (Figure 6.15) extending approximately 20 km to northwest-southwest-southeast and 10 km to the northeast. There are no registered bores identified as intercepting the Walloon Coal measures within the 1 m drawdown area, but one of the two registered bore recorded as intercepting the Westbourne formation lies on the limit of the 1 m drawdown limit. Water levels then recover to near pre-operational levels by 2 years after the end of the cleanup. (Figure 6.16)
Figure 6.12: Plan of water levels at end of gasification

Figure 6.13: Plan of drawdown at end of gasification
Figure 6.14: Plan of water levels after cleanup

Figure 6.15: Plan of drawdown after cleanup
Figure 6.16: Plan of water levels two years after cleanup

Figure 6.17: Plan of coal seam; Increase in salt concentration after 20 years
6.3.3 Transport of contaminants from the UCG panels

During the gasification and cleanup stages, the pressure within the cavities is kept below the pore pressure of the surrounding groundwater. Thus contaminants cannot leak out from the cavities during these stages against the pressure gradient. However, after the cleanup stage, any contaminants remaining in the cavities can escape the cavities and it is this stage that will be considered here.

Two types of contaminants were considered: salt and benzene. Salinity modelling indicates that salinity does not increase in groundwater outside a 100m radius of the cavities by more than 100mg/L. The maximum radius occurred 20 years following cleanup (see Figure 6.17), after which the radius decreased, with no concentrations more than 100mg/L above background after 100 years.

For benzene contamination, only advection and dispersion were modelled as insufficient data were available to determine adsorption factors, and biological decay may be slow under the anoxic conditions likely to be present within the aquifers. These assumptions allow for a conservative estimate of the upper levels of contamination concentration and transport rates likely to occur.

Benzene contamination does not migrate out of the immediate UCG cavity until water levels recover to the extent that the previous south-westward hydraulic gradient is re-established. This occurs about 10 to 20 years following cleanup when the benzene plume (where concentration exceeds 0.001mg/L) extends 100m to the south-west in the coal seam and reaches the lower Springbok Formation. At approximately 100 years after commencement of the post-cleanup stage, the benzene plume extended approximately 300m to the southwest of the UCG modules in the lower Springbok Formation (see Figure 6.18). Throughout the modelled period, concentrations were higher within the coal seam (see Figure 6.19), but the extent of the plume greater than the 0.001 mg/L trigger value was greatest in the lower Springbok Formation after 100 years. After 200 years the plume extends approximately 600m to the southwest (see Figure 6.20 and Figure 6.21). After 1000 years the plume of benzene concentrations above the 0.001 mg/L trigger value extends approximately 2000m to the southwest in the Springbok Sandstone (see Figure 6.22 and Figure 6.23), given the assumptions of constant contaminant release and no contaminant removal by reaction or adsorption.
Figure 6.18: Plan of lower Springbok Formation; Benzene concentration after 100 years

Figure 6.19: Plan of Coal Seam; Benzene concentration after 100 years
Figure 6.20: Plan of lower Springbok Formation; Benzene concentration after 200 years

Figure 6.21: Plan of Coal Seam; Benzene concentration after 200 years
Figure 6.22: Plan of lower Springbok Formation; Benzene concentration after 1000 years

Figure 6.23: Plan of Coal Seam; Benzene concentration after 1000 years
6.3.4 Surface subsidence and caving

The local model predicts ground displacement following the removal of coal due to the gasification. The gasification is assumed to leave approximately 20% ash and char by volume, so the expected closure in the cavity (if and when full caving occurs) is 8m of the assumed 10m thick seam.

Extraction of elements to simulate the gasification is done in ten large steps. With the larger cavities of cases 1 to 7, the step is 60m and roof caving is predicted from the third step (i.e. between 120m and 180m of gasification). Figure 6.24 to Figure 6.26 show the base case rock vertical displacement at various stages of gasification on a half-model, where half of the model is removed to enable the vertical section midway down the centre of the inner panel to be seen. There is a vertical exaggeration factor of 6 in these figures. The zone where rock is predicted to fail (and therefore undergo large deformations) can be seen to increase in height and width as the gasification progresses.

Figure 6.24: Predicted vertical displacement (m) after 180m of gasification
Figure 6.25: Predicted vertical displacement (m) after 360m of gasification
Figure 6.26: Predicted vertical displacement (m) after 600m of gasification

The evolution of the predicted subsidence at the surface on a section perpendicular to the direction of cavity creation and above the current midway point of the cavities is shown in Figure 6.27. The different lines show predicted subsidence after each of the ten gasification stages and after the final clean-up. The post-clean-up maximum subsidence at the surface is predicted to be 0.45m.

The predicted exaggerated surface subsidence profile is shown in Figure 6.28, where a vertical exaggeration factor of 400 has been used.
Figure 6.27: Evolution of subsidence profile as gasification progresses

Figure 6.28: The surface subsidence profile with a vertical exaggeration of 1, 20 and 400
The shapes of the subsidence profiles for the variations with three cavities are predicted to be similar to that shown in Figure 6.27 and Figure 6.28. Subsidence is only apparent with significant vertical exaggeration. The predicted maximum subsidence following the clean-up for each of the variations is listed in Table 6.6. The maximum predicted subsidence is greater with the fewer cavities. This suggests that subsidence in a region with many cavities may be highly dependent on the gasification sequence. As expected, the predicted subsidence is much less with the smaller cavities of case number 8, where roof caving is not predicted. The maximum predicted roof vertical deformation for this case is 0.4m after clean-up and 0.04m after the final gasification stage, while the 3MPa gas pressure is maintained in the cavity.

Table 6.6: The maximum predicted subsidence in different cases with the local model

<table>
<thead>
<tr>
<th>Case number</th>
<th>Description</th>
<th>Maximum predicted subsidence (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Base case</td>
<td>0.45m</td>
</tr>
<tr>
<td>2</td>
<td>Base case with cavity gas pressure reduced to 2.5MPa (instead of 3MPa)</td>
<td>0.47</td>
</tr>
<tr>
<td>3</td>
<td>Case 2 with the water table level 70m below the surface (increased from 20m)</td>
<td>0.45</td>
</tr>
<tr>
<td>4</td>
<td>Base case with all rock permeabilities reduced by a factor of 10</td>
<td>0.46m</td>
</tr>
<tr>
<td>5</td>
<td>Case 2 with all rock permeabilities reduced by a factor of 10</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Base case with gasifications in only the outer two cavities</td>
<td>0.60</td>
</tr>
<tr>
<td>7</td>
<td>Base case with gasification only in the inner cavity</td>
<td>0.63</td>
</tr>
<tr>
<td>8</td>
<td>Base case with alternative cavity layout design</td>
<td>0.08</td>
</tr>
</tbody>
</table>

The opening of joints and rock failure in the roof leads to increased permeability. Figure 6.29 shows the predicted exponential increase in vertical permeability in the rock above the UCG cavities at the end of the gasification. For instance, a value of 2 would indicate an increase in permeability by a factor of $10^2 = 100$. These increased permeabilities are used when estimating flow in both the local and regional models.
6.4 Conclusion

Numerical models have been used in the initial assessment of some issues associated with UCG, including the inflow of water into the gasification cavities, the drawdown and impact on regional water flow, flow of contaminants from the gasification site and surface subsidence. Two different models were used: a local model (see Section 6.2.1) that included mechanical effects to investigate water inflow during the gasification and clean-up, local drawdown during the gasification and surface subsidence and a regional model (see Section 6.2.2) to investigate water inflow, drawdown, impacts on regional flow and the possible flow of contaminants. A possible site for UCG was selected within the Eastern Surat Basin (on the basis of availability of some geotechnical information rather than any perceived optimality) and used as the basis for the modelling. The model assumed three parallel cavities 600m long, 180m wide and 10m thick, separated by pillars of width 60m, at a depth of 390m. A number of variations (listed in Table 6.3) were considered with the local model, including an option with smaller cavities, to help assess the impact of uncertain parameters on model results.
The principal findings of the investigation are:

The rate of water inflow into a UCG cavity increases as the cavity grows and is higher for outer cavities compared to the inner cavities of the gasification region. Average water inflow rates of up to 0.7 m$^3$/tonne of coal gasified were predicted for the outer cavities in the base case, but this estimate is sensitive to the detailed characteristics of the surrounding aquifers and the gasification plan, including the relative timing of gasification in different cavities.

Local water table drawdown of up to 17m was predicted during gasification in the base case at the UCG location, but the UCG operations had greater impact on pore pressure at greater depths (e.g. 55m at about 400m depth) where replenishment was slower. The extent of the drawdown greater than 0.5m (barely detectable) was predicted to be at most 10km from the UCG site during gasification and 20km during cleanup (although this would be reduced to about 10km with a revised cleanup plan). The cleanup plan as modelled is excessive, as it pumps out water at 6 times the rate that it is removed in the gasification phase for the 2 years of the cleanup phase. It was envisaged in the initial specification that the water inflow rate would be much lower than this, based on results of the Chinchilla trial. In a revised plan, which could be refined through iterative use of the models prepared in this study, water would be pumped out at a similar rate to that at the end of gasification to avoid drawdown, and the cavities would be flushed only once or twice to avoid water disposal problems and excessive aquifer depletion. The water drawdown predictions made in this study are exaggerated compared to what would be expected when using a refined cleanup plan but, despite this, water levels were predicted to return to their pre-gasification levels within approximately 2 years following cleanup.

Salt concentrations of 100mg/L or more above background were predicted only within a radius of 100m from the cavities. The peak radius occurred about 20 years after cleanup and after this the affected radius decreased. After 100 years, salt concentrations were predicted to be less than 100mg/L above background everywhere in the region.

Benzene concentrations above the 0.001mg/L trigger values reach an extent of 2 km to the southwest of the UCG modules in the Springbok Sandstone at 1000 years after cessation of the active cleanup stage, due to continuous replenishment from the cavities. At 100 years after cessation of cleanup the extent of the benzene above standard laboratory levels of reporting extends approximately 300m to the southwest of the UCG modules. The implication of this is that it will be difficult to prove that contamination will not occur in the long-term using short-term (up to 20 years) monitoring results after cleanup when contaminants are continuously replenished from a dense non-aqueous phase liquid in the cavities. These findings are strongly influenced by some conservative assumptions used in the modelling, namely that the source of contamination does not decay with time and benzene is not adsorbed or oxidised during dispersal. Omission of these decay mechanisms makes the eventual appearance of detectable levels of benzene inevitable in the models, but it is not possible to justify models of contaminant behaviour until more experimental data is available.

Surface subsidence of up to 0.45m was predicted in the base case, with greater subsidence predicted in the variations (up to 0.63m). The cavity roof was predicted to fully cave after about 100m of the 600m length of the gasification cavities in the base case. This extent of subsidence is not expected to have significant impact on land use (typically grazing) at the site selected after operations have completed.

The case study with multiple small cavities had significantly lower average total water inflow rates, but the average inflow rate into the outer cavities was greater than for the base case (up to 1 m$^3$/tonne of coal gasified). This case was also predicted to have much less subsidence (up to 0.08m during clean-up) and the cavity roof was predicted not to cave, so this represents a design that might be applied at sites where subsidence impact needs to be minimised.
7 SOCIAL AND LEGISLATIVE CONTEXTS

Any evaluation of barriers to UCG needs to consider the frameworks that will determine the acceptability of UCG to society. These frameworks can be formalised (typically in the form of regulation) or informal (based on the way society structures itself and the perceptions and choices that individuals make in a democratic country and a free market economy). The strong sustainability agenda operating within Australia demands that new technologies be developed in a manner that demonstrates a keen awareness of these contexts and the issues that arise from the interactions between science and society. These socially defined issues will influence the extent to which environmental impacts are seen as barriers to technology development.

Within this report, the term “social issues” is used to describe societal processes, features or relationships that have a bearing on, or are affected by the development of Underground Coal Gasification. For any technology, social issues can arise because of the manner in which UCG will impinge on peoples lives (direct impacts), because of the immediate concerns and needs of society (public perceptions and attitudes) and also because of the way society is structured to make decisions about what is in our best interests (governance and regulation).

This chapter provides an overview of the (formal and informal) social issues surrounding UCG. An analysis of the social issues relevant to UCG and the legislative context for a UCG development in Queensland is presented, together with an initial study into public attitudes to UCG based on Focus Groups in Country Queensland and Brisbane. Ways of understanding and addressing these issues in future research into UCG are also put forward.

7.1 A framework for considering the social and legislative issues

UCG is an emerging technology. As the research progresses, the extent of financial, personal and corporate investment increases. Decisions are required about whether to continue investing in the technology. These decisions need to take into account the risks inherent in the technology. There are many facets to risk but a key concern is that the technology will fail. Different people will have different views on what constitutes failure. As well as failing because of disfunctionality or a lack of economic return, technology can fail because of unacceptable environmental damage, social backlash or failure to meet permitting criteria. An important constraint on technology development is the definition of environmental acceptability and the characteristics of permitting criteria. These are socially determined and hence social issues are increasingly being considered alongside technical feasibility and economic viability in making investment decisions.

Figure 7.1 reflects contemporary thinking about “analytic-deliberative” models of decision-making (Fineberg and Stern (1998)) and identifies three components for addressing social issues in technology development:

- Technology – developed by a process of scientific research to meet a perceived societal need;
- Governance – the institutional structures which are used to bring order to society and provide “checks and balances” on individual components;
- Society – whose needs are supposedly represented by those in Governance and addressed through technological advancement
Figure 7.1: A three component model of social issues in technology development

The interactions identified on all three of the axes in Figure 7.1 can have a bearing on the “riskiness” of project arising from social factors – the potential role of the technology in society, its acceptance by society and the ease with which it can gain the necessary approvals from Government. The flow of information between the three components is fundamental in establishing the necessary confidence that the technology will be controlled and managed effectively. In particular, issues arising the technology-social and the technology-government axes could be significant influences in identifying technological options for addressing and mitigating environmental impacts.

To date, interactions along the technology-society axis have tended to be informal. They occur if voluntarily undertaken by the technology developer or if forced by community agitation. Some formal interactions occur, when required by legislation, but developing thinking about the role of dialogue in building trust advocates increasing levels of informal interactions along this axis from the earliest stages of a project. In part this is because these interactions are dominated by consideration of impacts and by public perceptions of the technology, the technology developer and governance systems. In contrast, the interactions along the technology-Government axis tend to be formalised interactions that are embedded in legislation. Regulatory authorities exist to permit, monitor and enforce compliance with certain standards. The technology developer can provide policy options for consideration by those in Governance.

Using this framework, an initial assessment of social issues associated with UCG was undertaken and is summarised in the sections below.

7.2 Impacts and perceptions

Social impacts are outcomes of implementing a technology. UCG is innovative. It has not yet been applied on a commercial scale and is not a generally accepted part of the energy industry. As with any technologies that break new ground, there is little precedent for people to refer to when discussing impacts and benefits. Such precedent as there is resides in the UCG trials that have been conducted throughout the world. These trials have been primarily focused on assessing the feasibility of the technique under varying design and site conditions – not on demonstrating performance and evaluating impacts. Nevertheless, it is already apparent that UCG could have impacts at a global, national and local scale.
On a global scale, UCG is a fossil fuel based technology with resultant greenhouse gas emissions. The association of UCG with carbon storage could mitigate this impact and this issue is discussed further in Section 5. A less direct global impact arises because the international community have been researching UCG for many years. The implementation of a full scale process in Australia would affect Australia’s standing as an innovator in the world energy market. However, this impact would be mainly confined to the energy research community.

On a national scale, UCG will have a social impact because of the political debate about the pros and cons of fossil fuel utilisation. UCG is a source of fossil fuel energy. It could thus focus significant attention, both from those fundamentally opposed to fossil fuel use and from those who want to use fossil fuels in a better way. It is not clear where UCG would sit in this national debate about fossil fuels and global warming, particularly as CSIRO’s research into the greenhouse gas contributions of UCG is still underway. Nevertheless, it is reasonably clear that UCG would impact the energy markets in Australia by offering an alternative raw material for electricity generation or liquid fuel production.

On a more local scale, key issues to be addressed will be the environmental impacts of UCG and the public perception of the technology. The research described in this report is exploring whether the key environmental impacts can be managed and mitigated. However, the significance and acceptability of these impacts, however well managed, will vary depending on culture and background.

Some impacts to be considered include:

- **economic** – opportunities for employment (due to infrastructure and labour requirements associated with a UCG project); other economic changes that could arise from having UCG operating in a certain area
- **environmental** – there is a potential for groundwater contamination, in which case stock watering practices could be affected; other environmental impacts such as soil subsidence; possible unknown long-term impacts;
- **social** - aesthetics/amenity - visual and noise impact of any UCG operations and/or associated surface plant; other positive or negative image that society ascribes to the UCG process; psychological impacts due to perceptions of the benefits or disadvantages of UCG operating
- **cultural** – due to the influx of UCG technologists into an area

At a very basic level, the underlying principle of UCG could raise alarm in the minds of those considering the process. The idea of initiating gasification under the ground does not sit comfortably with the ideas that the earth needs to be preserved for future generations and that technology needs to be applied under controlled conditions. This basic mistrust is a matter of perception. Perceptions are a complex issue in today’s society.

Perceptions will affect the way in which different people view the outcomes of a project. People’s perceptions are conditioned by their level of familiarity with a subject and by their values. Values are a way of describing the relative importance of different issues, commodities or behaviours. Different people have different values and these values drive their aspirations and will be a major influence on what individuals will consider acceptable in any new development. Values are often culturally instilled and then subtly modified by life experience. There is little that can be done to influence value systems.

However, another important contributor to perceptions about technology is belief. Unlike value systems, beliefs are almost exclusively developed through experience. This may be either direct or indirect experience (i.e. someone else’s opinion). Because they are experiential, beliefs can change with subsequent experience.

So perceptions about UCG will be based on values and beliefs. Some individuals will form an opinion about its acceptability based on values alone. Others will be looking for experience to help guide their judgements. Where the technology is new or has little precedent (as is the case with UCG) this experience may arise:

- directly, based on experiences of projects that are seen to have similarities:
indirectly from people who are felt to have the necessary experience.

For UCG analogies are likely to be drawn with experiences from mining, coal bed methane, previous trials of UCG and extractions from oil shales. The environmental impacts of previous UCG trials have been reviewed by Mark and Beath (2004). Experiences from the Stuart Oil Shale project and from the Coal Bed Methane projects would need to be examined to identify the public perceptions of environmental impacts that will condition responses to UCG.

However, it is generally indirect experience that provides the basis for many individual’s perceptions of new technologies. An individual is most likely to listen to the “voice of experience” from someone they trust. The academic literature on trust offers many insights into who trusts whom and why (Frewer and Lofstedt (1998)). This is an area where there is vast opportunity to influence public perceptions - opportunity that is exploited by both opponents and proponents of any new technology. If trust is the key to influence, then influencers need to carefully consider the processes that build trust between two parties. This inevitably leads to a consideration of relationships, relationship-building and reputation management. These will be important issues to consider for the development of UCG – what relationships, how can they be built and protected and what reputation is being established?

7.3 Public attitudes to UCG – an initial survey

Whilst researchers can attempt an analysis of social impacts, inherent biases and subjectivity means that no researcher can place themselves directly in the position of the uninformed public. Public participation is increasingly considered as one way to complement the expert analysis of social impacts. Public participation can highlight previously unrecognised social, economic, cultural and environmental impacts based on consultation and dialogue with potentially affected parties. Additionally, it can begin to establish the priorities with which the public view different aspects of a new technology.

A scoping study of public attitudes to UCG was undertaken to complement the analysis of social issues presented above. The survey and its outcomes are described below.

7.3.1 Method

In order to identify the public perceptions of UCG, a survey of attitudes to the technology was conducted. Two public focus groups and an expert group were convened by an independent facilitator. At each group, participants were asked about the benefits they saw arising from UCG technology and also about the concerns that they had with the technology.

**Expert Group**

This group comprised members of the project team working on underground coal gasification technology within CSIRO. An external expert representing Linc Energy was also invited to present an industry perspective.

**Public Groups**

Two separate groups were undertaken, one in Brisbane and one in Roma. The locations were selected to allow initial comparisons between country Queensland and the city. Participants were recruited through advertisements although in Roma the group was created partly by word of mouth from an initial recruit.

**Level of knowledge and prior information**

The expert group was extremely knowledgable. For the public groups, prior information was kept deliberately poor. An initial 5 minute description of UCG was provided by a CSIRO researcher who then observed the process but did not respond directly to questions unless requested by the facilitator. The idea was to develop a baseline of perceptions.
**Format**
In all groups, after a short introduction the participants were asked to spend a few minutes writing down the benefits they could see arising from the implementation of UCG. The facilitator then encouraged participants to articulate these concerns on a round table basis.

Subsequently, participants were invited to consider the concerns that occurred to them when they thought about UCG. The same process was used to enable these concerns to be articulated and discussed amongst the Group.

**Reporting**
After completion of the Focus Groups the Facilitator independently summarised and classified the benefits and concerns expressed by each Group. The results are given in the tabular presentations below (Table 7.1, Table 7.2 and Table 7.3).

### 7.3.2 Results
A number of the issues that were raised during the public Focus Groups arose simply because of lack of information. Many points could have been addressed quite simply during the Focus Group process by the presence of an individual familiar with the technology. A key point from both Groups was that people were interested and keen to have more information.

**Table 7.1: Collated results from the Expert Group**

<table>
<thead>
<tr>
<th>Benefits of UCG</th>
<th>Prospective concerns with UCG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Better way of exploiting Australia’s coal reserves</td>
<td>How safe is it?</td>
</tr>
<tr>
<td>Economic benefits to Australia</td>
<td>What impact will it have on people’s property?</td>
</tr>
<tr>
<td>Economic benefits to regional economy</td>
<td>What will be the visual impact?</td>
</tr>
<tr>
<td>Environmentally beneficial</td>
<td>What about the impact on the environment?</td>
</tr>
<tr>
<td>Benefits to Australian community &amp; Australian industry</td>
<td>Is it really economically beneficial?</td>
</tr>
<tr>
<td></td>
<td>Will we be kept properly informed?</td>
</tr>
<tr>
<td></td>
<td>Are there any examples where it’s been done successfully?</td>
</tr>
<tr>
<td></td>
<td>Aren’t there better ways of investing in emerging energy sources?</td>
</tr>
<tr>
<td></td>
<td>Can we really do it successfully?</td>
</tr>
<tr>
<td></td>
<td>Who’s regulating all this?</td>
</tr>
</tbody>
</table>

**Table 7.2: Collated results from the Brisbane Focus Group**

<table>
<thead>
<tr>
<th>Benefits of UCG</th>
<th>Prospective concerns with UCG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Better way of exploiting Australia’s coal reserves</td>
<td>How safe is it?</td>
</tr>
<tr>
<td>Economic benefits to Australia</td>
<td>Who’s monitoring / controlling things overall?</td>
</tr>
<tr>
<td>Economic benefits to regional economy</td>
<td>What impact will it have on people’s property?</td>
</tr>
<tr>
<td>Environmentally beneficial</td>
<td>What about the impact on the environment?</td>
</tr>
<tr>
<td>Benefits to Australian community &amp; Australian industry</td>
<td>Is it really economically beneficial?</td>
</tr>
<tr>
<td></td>
<td>Will we be kept properly informed?</td>
</tr>
<tr>
<td></td>
<td>Aren’t there better ways of investing in emerging energy sources?</td>
</tr>
<tr>
<td></td>
<td>Who’s really going to benefit from this, and when?</td>
</tr>
</tbody>
</table>
Table 7.3: Collated results from the Roma Focus Group

<table>
<thead>
<tr>
<th>Benefits of UCG</th>
<th>Prospective concerns with UCG</th>
</tr>
</thead>
<tbody>
<tr>
<td>· Better way of exploiting Australia’s coal reserves</td>
<td>· How safe is it?</td>
</tr>
<tr>
<td>· Economic benefits to Australia</td>
<td>· Who’s monitoring / controlling things overall?</td>
</tr>
<tr>
<td>· Economic benefits to regional economy</td>
<td>· What impact will it have on people’s property?</td>
</tr>
<tr>
<td>· Environmentally beneficial</td>
<td>· What about the impact on the environment?</td>
</tr>
<tr>
<td>· Benefits to regional community</td>
<td>· Is it economically beneficial to the region?</td>
</tr>
<tr>
<td></td>
<td>· Will we be kept properly informed?</td>
</tr>
<tr>
<td></td>
<td>· Aren’t there better ways of investing in emerging energy sources?</td>
</tr>
<tr>
<td></td>
<td>· Who’s really going to benefit from this, and when?</td>
</tr>
<tr>
<td></td>
<td>· Don’t believe that politicians, scientists or business will be truthful with us</td>
</tr>
</tbody>
</table>

7.3.3 Analysis

Although many of the same issues arose in both the Brisbane Focus Group and that conducted in Roma, there was a marked difference in emphasis. In Brisbane, more awareness of a national energy need was expressed, together with some cosmopolitan ideas about global risk and the need to do things to benefit society as a whole. For the people at Roma, the most important issues revolved around what economic advantages or infrastructure developments, such as a hospital, could be brought to their town by the technology. The Roma participants were interested in what UCG might bring to their community, rather than to Queensland or Australia as a whole. In both groups, most of the issues and concerns were expressed in the form of questions, reflecting an extremely low level of awareness of the issues surrounding coal technology in general. However, in Roma, participants made strong statements expressing a profound distrust of politicians and businesses who might be thinking of moving in to the area. This appeared to be related to past experiences and was a generic concern rather than one relating specifically to the concept of UCG.

Both public groups expressed some concerns about pollution, but the definition of pollution or contamination was vague. Surprisingly, neither group talked much about global warming or greenhouse gases. Additionally, concerns about groundwater emerged only late in the discussion. These findings contrast significantly with the results of the Expert Group discussion, which articulated specific issues of environmental impact as the first concerns with UCG. This is not surprising given that the expert groups was largely comprised of researchers who are looking specifically at the environmental issues relating to UCG.

In general, the survey highlighted some important areas for information provision and discussion in any future attitudinal research. It also identified that the public is able to engage sensibly with the topic of UCG, even from a point of very little knowledge. The groups were able to identify potential benefits as well as prospective concerns, and in all cases the dialogue was constructive. The environmental issues raised by the public participants aligned well with the issues raised by the expert group, suggesting that the environmental research described in this report is well aligned with the issues of concern to society and will be of direct use as a knowledge base for any further dialogue.

7.4 Government and policy context

The context for researching UCG will be provided by global debates about sustainable energy production and climate change, national debates about security of future energy supplies, industry level debates about regulation and competition and community level debates about local impacts. Governmental responses to these debates will have an effect on the desirability of UCG as an option for producing energy into the future. For example, UCG is a gasification process. Surface gasification (using mined coal) is also under consideration as a “clean” use of coal for power generation. The relative performance of these two technologies in terms of greenhouse emissions, other environmental risks and economics may determine the viability of UCG in the minds of both Governments and the market place. Technical evaluations of the
greenhouse gas emissions are presented in Section 5 and show that in some configurations UCG processes could provide a cost effective means of significantly reducing Greenhouse emissions compared to current electricity generation technologies.

As well as establishing energy policy, Governments have a responsibility to regulate energy provision. The regulatory regime for UCG is immature. Whilst trial processes have been authorised in Queensland, a full scale proposal has not yet been advanced. The regulatory regime to govern such a full scale proposal is not clear, which could be a major barrier to advancing any future proposal for developing UCG.

UCG is an alternative to coal mining. It is therefore likely that the regulatory regime for UCG will evolve from that already in place for coal mining. The Australian mining industry is already in the process of responding to global visions of sustainable development and is currently putting in place a number of initiatives for self regulation and codes of practice for social and environmental management (Mark and Beath (2004)). Whilst several different ways of formulating and implementing the principles of sustainable development have been put forward, they share certain characteristics that could have a major influence on the processes by which UCG is developed.

- Transparency and access to information
- Inclusion and empowerment
- Making decisions locally (subsidiarity)
- Minimising waste and damage
- Preserving biodiversity

These voluntary developments within the mining industry sit alongside the existing and formal regulatory regimes that operate to control the industry and protect the environment. As the likely site for the first project for UCG in Australia is in the State of Queensland and with a current project active at Chinchilla it is appropriate to discuss regulation and approval in the Queensland legislative context. In other states the process will vary but the outcomes will be very similar.

### 7.4.1 Queensland legislative framework

As a general trend the regulatory framework governing environmental performance of mining in Queensland has stayed away from prescription favouring instead a model where the proponent proposes a management plan and the criteria that they will commit to and those criteria are assessed by the Environmental Protection Agency (EPA) and either approved or negotiated. Depending upon the trigger levels of various pieces of legislation these criteria are publicly tested through an Environmental Impact Statement process or are developed through a process of negotiation which results in an Environmental Authority issued by the EPA which carries the compliance conditions. In this framework compliance is measured as much on the compliance with the plan as it is in achieving the designated outcomes.

UCG is considered a mining process by the NRM&E (QLD) and as such will be administered in the same way as a coal mining project. As a mining process UCG is regulated through legislation at a state level by the Mineral Resources Act 1989 (MR Act), Environmental Protection Act 1994 (EP Act) and the Environmental Protection and Other Legislation Amendment Act 2000. In terms of Environmental Impact Statement (EIS) requirements an EIS may be triggered at a state level by the requirements of the EP Act, State Development and Public Works Organisation Act 1971 (SDPWO Act) or federally by the Environmental Protection and Biodiversity Conservation Act 1999 (EPBC Act).

As an example the Chinchilla project has developed through the trial stage under the procedures set out in the Environmental Protection (EP) Act and the Mineral Resources (MR) Act under a Mineral Development License. The scale of the project didn’t trigger any requirement for an Environmental Impact Statement ((EIS) and was managed under an Environmental Authority issued by the
Environmental Protection Agency (EPA) and a Minerals Development Licence (MDL) issued by the Department of Natural Resources Minerals & Energy (DNRME).

There are no existing environmental regulations or policies that are specific to Underground Coal Gasification. However, a large number of Codes of Practices and Guidelines have been developed for various aspects of the mining process and for environmental management in general. These are generally taken as de facto regulation when specifying environmental performance criteria. Australia New Zealand Environment Council Guidelines are almost de facto regulations in that they are often used by EPA to set emission limits. However, Underground Coal Gasification has been considered by NRM&E and amendments to legislation have been drafted into the Mineral Resources and Other Legislation Amendment Bill to include UCG in the MR Act for the purposes of tenure administration but to allow for Petroleum Act safety requirements and operational procedures to be applied.

In summary, in Queensland there appears to be no legislative barriers to UCG that are unique. Applying documented management practices as demonstrated at the Rocky Mountain (USA) and Chinchilla (Australia) trials is highly likely to be sufficient to comply with existing environmental performance guidelines.

### 7.4.2 Groundwater Criteria

Looking to the potential environmental impacts of UCG, the majority are analogous to the impacts of other mining and petroleum projects. The exception is the impact of groundwater. Hence the legislative framework for groundwater contamination from UCG bears further consideration.

A core assumption of the environmental management process and sustainable development is that the UCG project will not impact adversely upon the environment in a way that limits the opportunities of future generations. As an example UCG will not be allowed to impact on the long term viability of the groundwater resource, so criteria will be set to protect the usability of the groundwater to whatever quality it currently has. Those criteria will apply to the lease boundary and any discharges off lease (air, surface water, groundwater, noise, etc.) during operation and will apply to the rehabilitated lease at relinquishment. Impact is allowed to occur so long as that impact is mitigated and can be rehabilitated so as not to have any effect off-lease, and on-lease at relinquishment.

**Groundwater Use**

Groundwater is recognised as a valuable resource that must be protected from degradation. It is acceptable to extract groundwater provided that its use adheres to the principals of Ecologically Sustainable Development (ARMCANZ 1996). The most significant impact that UCG will have is that it is a consumer of groundwater. A conservative estimate is that the process itself will consume between 0.25 and 1 tonne of groundwater per tonne of coal gasified. Groundwater use for a large scale UCG project will be one of the criteria that triggers an EIS process. Groundwater consumption, and quality impacts by the coal mining industry has also recently been raised as an issue for underground mining.

Any project that abstracts 2 million tonnes per year of run of mine ore and/or 2 million m$^3$ or more of groundwater or surface water requires an EIS (QEPA 2000).

Acceptable groundwater use will depend upon the quality of the water resource that is being used, its alternative uses and the impact that use will have on other users and potential future users. Site specific issues are very critical in developing acceptable criteria. Fortunately for the UCG process, the quality of the groundwater has little impact on the UCG process, therefore poor quality groundwater is actually a positive selection criteria for UCG.

No specific guidelines or criteria have been established for ground water consumption in coal mining. Preliminary modelling suggests UCG will extract an amount comparable and most likely less than competing coal utilisation technologies such as longwall mining or coal seam methane extraction. Water
use and management has recently been identified by regulators and the mining industry as a significant issue for the mining industry in general and has been identified by ACARP as a priority area for research.

In the majority of cases water contained in the coal seam itself is saline to varying degrees and in-fact the major concern for mining and coal seam methane is how to deal with this saline water once it is brought to the surface through dewatering requirements. In the case of UCG the salts are left underground and the water that is brought to the surface as part of the gas flow is condensed out and is low in mineral content. A significant difference between coal seam methane, underground coal mining and UCG is that UCG brings the water to the surface as steam which when condensed doesn’t carry the minerals with it (its not salty) whereas both CSM and Underground coal mining bring saline water to the surface, which is a substantial impact. On the other side of the coin the salinity of the aquifer in the vicinity of the gasification will increase post gasification as the extra salt is left behind. Salinity is a serious issue which regulators are addressing and will be an issue for any new project in inland areas of Australia.

A potential solution to the groundwater problem for UCG is re-injection (not feasible for mining and CSM) but this will require substantial investigation as to how and what the risks are and development of management plans and performance criteria for re-injection. This is very much a new concept for regulators in Queensland.

**Groundwater contamination**

In order to put groundwater contamination from UCG into context with environmental protection guidelines, Table 7.4 compares guidelines from various sources with measured contamination levels from UCG trials.

Keep in mind that environmental guidelines apply at the receptor while the levels reported for UCG trials are in the cavity or in nearby monitoring wells. In the case of the operating UCG site all environmental performance guidelines will only apply to discharges at the lease boundary and will only apply on the lease area after relinquishment. One of the control strategies is to ensure that during operation the lease area is large enough so that any contamination does not escape during the lease boundary. After the project is completed then remediation and verification can commence to ensure that the lease area is cleaned up to meet standards. This is currently how the mining industry operates to control its discharges by allowing for a lease area large enough to contain tailings dams etc./ which, are capped and left as permanent features at the end of mining.

In general, inorganic compounds are not considered a serious problem as they return fairly quickly to background levels as ground water returns to the gasification cavity however over a long period of operation the concentration of mineral salts in the groundwater over a large area could affect the potential use of the water. UCG will not be allowed to permanently degrade the potential use of groundwater.
Table 7.4: Contamination level comparisons

<table>
<thead>
<tr>
<th>Key compounds</th>
<th>Benzene (mg/l)</th>
<th>Phenol (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANZECC Drinking Water</td>
<td>0.001</td>
<td>N/A</td>
</tr>
<tr>
<td>ANZECC Ecosystem</td>
<td>0.3</td>
<td>0.05</td>
</tr>
<tr>
<td>USEPA Drinking Water</td>
<td>0.005</td>
<td>4</td>
</tr>
<tr>
<td>USEPA Ecosystem</td>
<td>N/A</td>
<td>3.5</td>
</tr>
<tr>
<td>ANZECC Soil Investigation Lever</td>
<td>8500 mg/kg</td>
<td></td>
</tr>
<tr>
<td>Chinchilla Trial--Cavity</td>
<td>0.010</td>
<td>0.3</td>
</tr>
<tr>
<td>Chinchilla Trial Perimeter Well</td>
<td>(ND)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Pricetown Trial Deep Well Post Test</td>
<td>N/A</td>
<td>1.2</td>
</tr>
<tr>
<td>Hoe Creek Post Test</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Day 3,</td>
<td>1</td>
<td>450,</td>
</tr>
<tr>
<td>83,</td>
<td></td>
<td>20,</td>
</tr>
<tr>
<td>280</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Hoe Creek II/II Post Test Max</td>
<td>N/A</td>
<td>0.75</td>
</tr>
<tr>
<td>RM1 Test, Post test max in ground water</td>
<td>ND</td>
<td>0.75</td>
</tr>
</tbody>
</table>

The findings from this review of Queensland legislation suggest that there are few barriers or criteria against in formal regulation and legislation against which to judge the environmental performance of UCG. This does not mean that there can be an assumption that UCG has acceptable environmental impacts. Because it is relatively new to the market place and to the public, acceptability will be a matter for discussion and negotiation. Addressing some of the informal social issues identified above will need to be part of that discussion and negotiation if UCG is to demonstrably overcome the environmental and perceptual barriers.

### 7.5 Addressing social issues

Both the analysis of social issues and the findings of the public attitudes survey identify a range of linked concerns about the environmental impacts of UCG and the viability of the technology. A major focus of both the analysis and the survey results is on the impacts of UCG - potential changes to the way people live and the way society is structured should UCG be developed and implemented. Social impacts are outcomes of the project. The public develop perceptions about those impacts and Governments seek to regulate the impacts.

There are also the other issues identified in the survey that are best described as social interests. An “interest” is defined here as a need or willingness to influence the development and implementation of UCG. Social interests can contribute to the technology development process. The extent to which they contribute is dependant on the relationships that are built up between different interest groups. These relationships will also be important in determining perceptions of a new technology and in influencing the development of a regulatory regime.

Social impacts and social interests are both necessary to any consideration of technology and its role in society. Two broad approaches have been considered for addressing them in UCG research and development:

- Assessment techniques - to establish and quantify social impacts
- Dialogue - to understand and inform social interests

#### 7.5.1 The role of assessment

Environmental regulation and permitting commonly call for risk assessments or impacts analyses as part of the permitting process. A range of assessment techniques and tools have been developed over the last few decades and increasingly such assessments incorporate participation within their framework. Such
techniques are developing rapidly and help researchers understand a range of potential impacts generated by a project or development. Some of the methods are particularly attractive for UCG:

- Life cycle analysis offers the potential of comparing the impacts of UCG with those of its competitors (coal mining, coal bed methane, surface gasification) on a like for like basis. However, reputable coal mining and CSM life cycle assessments could need to be found for the comparison.
- UCG is not yet at the stage of requiring an Environmental Impact Assessment – which is generally developed for a specific project at a specific place. Nevertheless an EIA (to produce an environmental impact statement or EIS) will be required for the development of UCG at a particular site. It will be important to learn from experience about how to go about the EIA. There are now many documented examples where an evolving and transparent process of impact assessment culminating in an EIA has been better received than a “just in time” approach to preparing an Environmental Impact Statement.
- Strategic environmental assessment (SEA) offers a method for analysing the impacts of UCG across the social, political, environmental and economic domains without having to commit to a particular design specification and a specific location. Strategic Environmental Assessment is increasingly being used in Europe and has many similarities with Sustainability Assessments which are more familiar in Australia.
- Social Impact Assessment is another method that would be suitable for the current stage of the UCG project. However, it can be rather limited in its scope unless a conscious decision is made to incorporate environmental issues. Social impact assessment is receiving increased attention in the resource extraction sector. A recent review of assessment applications in the mining industry concluded that they were generally applied in order to meet permitting requirements, rather than as a management tool to inform decision making about the course of a mining development.

In the case of UCG, there is an opportunity to integrate these assessment tools early into the technology development process. The development of an environmental assessment that includes a social impact component and is then used in an iterative manner to support various stages of future UCG research and development is advocated, as shown diagrammatically in Figure 7.2. The research presented in this report can be used as the baseline for an initial assessment and can subsequently be refined as more detailed and site specific knowledge becomes available. Each assessment can be used to identify important areas for research in order to reduce continuing and significant uncertainties about environmental impact. The significance of these continuing uncertainties can in part be determined by their significance to various sectors of society.
7.5.2 The role of dialogue

Dialogue can be undertaken because it is deemed to be an important part of developing a technology project, because it is required for the permitting process or for some combination of the two. Dialogue is most effective when it is undertaken freely, rather than imposed and when it is used as a continuing process to inform the management of all stages of a project. Best practice in dialogue also includes the idea that it is a two-way process - i.e. that it represents dialogue between all parties and that there is an intent to respond to the issues raised through the dialogue. For UCG this is an opportunity to shape the relationships between operator, community and Governments from an early stage and to explore the perceptions and values that will influence social attitudes to UCG as the technology develops.

Many models and ideas are proposed in the literature, which discuss methods and principles for participation, stakeholder engagement, consultation and deliberation (Beirle and Cayford (2002)). These models share the view that specific interest groups (stakeholders) exist and have an impact on (a stake in) the effectiveness of a business. This “stakeholder model” has evolved since the 80’s but the central premise remains the same.

Stakeholder groups can be classified in many ways but they share a willingness and an ability to act with the intent of affecting the business. Hence they have a social interest in the technology. It follows that organisations should be developing relationships with these stakeholders. Methods for stakeholder engagement have been analysed extensively in literature spanning the spectrum from marketing theory, business, operational analysis to sociology and psychology.

Dialogue is increasingly seen as a way of determining social interests and also managing social risk to a project – i.e. the risk that the project will be delayed or terminated because of community or regulatory objections. Many processes for dialogue can be considered. However, the success (or not) of dialogue is primarily determined by:

- ensuring that the methods are appropriate for the specific context being addressed (i.e. tailoring the dialogue process to the particular stakeholders and topic under discussion);
- the attitude of those undertaking the dialogue;
Many workers identify a spectrum of attitudes that can be adopted. They present options on a “Ladder of Participation” (Arnstein (1969)), shown in Figure 7.3, and encourage organisations to aspire to partnership. A goal for CSIRO should be to work out the extent to which levels 6, 7 and 8 are achievable for UCG and the actions that are required to achieve them. The concerns expressed in the public attitude survey about who benefits and the lack of trust exhibited by the respondents in Roma suggests that partnering should be the minimum level to which CSIRO aspires as it considers its role in future UCG research and development”.

Figure 7.3: Ladder of participation

7.6 Summary

In order to effectively address the social issues relating to UCG, a distinction between the social impacts of UCG (i.e. the outcomes of the project) and the social interests in UCG (i.e. the relationships that are important as the technology develops) is advocated. This would allow the project team to preserve their focus on impacts using participatory assessment techniques, and in so doing to cultivate relationships with key stakeholders and understand social interests. However, successful implementation of a participatory impact assessment approach has some key criteria:

- The assessment process is seen as a means to an end, where the end is a continuous and developing input of social values into decision making about UCG. This process should start as early as possible with an assessment of public attitudes to UCG.
- The research team needs to see the participation process as one of partnering with key stakeholders to make better decisions about UCG.

The assessment process(es) appropriate for UCG need to be identified so that any necessary research and relationship building can begin as early as possible. A key aim of such assessments is to describe potential outcomes which are measurable (qualitatively if not quantitatively) and hence amenable to reporting and performance monitoring. However, the significance of these outcomes is highly subjective. Peoples “values” will affect both what they think should go into the assessment and the way they interpret the outcome of the assessment. Best practice in the application of any form of participatory impact assessment (such practices generally emerge from natural resource management industries) would suggest that such assessment techniques be applied very early in the project and then be applied continually as a way of bringing social values into future environmental research into underground coal gasification.
8 DISCUSSION AND CONCLUSIONS

The study involved an analysis of the environmental barriers to large scale implementation of underground coal gasification (UCG) in Australia. There were two phases of the research project with this objective. The first was introductory work that established the existing technologies for UCG through a review of past experience worldwide, and then identified an apparently suitable site in the eastern Surat Basin in Queensland before developing a scenario of a nominal 400MWe electricity generation plant at the site as a base case for further analysis. The second phase was an analysis of the performance of the plant based around Greenhouse gas emissions, comparative economics, groundwater and subsidence impacts and the social and legislative issues of UCG. Summaries on each of these topics are available in the relevant sections of the reports and the following is a discussion of the overall performance of the plant based on these analyses.

8.1 Base scenario

The scenario developed was that of an approximately 400MWe electricity generation plant based on a UCG development in the eastern Surat Basin. The site was selected following on a review of previous UCG studies and an analysis of available coal resources in Australia, but there is a sparse scattering of data through most regions that appear suitable for UCG and the site could be best described as having tentative suitability. A detailed site characterisation study similar to that required for an underground mine would be required before a full UCG design could be performed for the site. A fairly simplistic design for the site was prepared to use in the modelling of site impacts and it is likely that this could be optimised to reduce the impacts and improve operational performance. UCG is an unusual process in that the design of the reactors can be modified quite simply during long term operation of site, as they have a relatively limited lifespan and new reactors are constructed on a regular basis. The reactors in the study were designed simply to remove large blocks of coal with a minimum of construction cost and were specified on assumed site behavioural characteristics, such as groundwater flow into the reactors. Some findings of this study suggest that improvements could be made in the design and operating conditions.

8.2 Greenhouse emissions and economics

The Greenhouse gas emissions for the UCG plant were analysed for three different plant configurations and two sets of UCG reactor performance characteristics covering a nominal range of UCG performance, along with the same plant configurations using a surface coal gasifier for comparison. The three configurations considered were a standard IGCC-type process, an IGCC process incorporating carbon dioxide removal and an IGCC process with a gas shift prior to carbon dioxide removal for each of the gasifier product gases. Comparative economic analyses of these plants were performed, as it is not practical to examine low Greenhouse emission plants without an indication of the costs involved in reducing emissions. The economic analysis did not consider the cost of sequestering the carbon dioxide that was removed, as this was considered to be outside the scope of the study. In brief, UCG as specified was not ideal as a low Greenhouse gas emission technology in standard IGCC form, however, it had significantly lower electricity costs compared to surface gasification and lower Greenhouse emissions when a carbon dioxide removal configuration of IGCC was considered. This appears an attractive option for low Greenhouse emission electricity from coal and the quality of the UCG gas has only a minor influence on the economics of the process. The version of IGCC using a shift reactor followed by carbon dioxide removal is very effective in reducing Greenhouse emissions for surface coal gasification, but not as effective for UCG sourced gas. In all cases it is an expensive process to build and operate and would be difficult to justify economically without a substantial subsidy in the current electricity market. In addition, the resultant high hydrogen content gas is not suitable for the existing generation of gas turbines.

The difference in performance of the UCG and surface gasifier sourced gases in gas turbine plant was greater than expected in these analyses. This is partly due to higher carbon dioxide content in the raw UCG gas, but gas turbine performance is also affected by the low total carbon content of UCG gas. The UCG product gas specified has a composition that is within the range of experimentally produced gases from previous trials, but there is considerable variability between these trials and it is possible that the UCG product gas from the site could be improved through variations reactor design and the operating
conditions. For example, prediction of the gas quality requires estimation of the water flow into the reactor relative to the coal consumption rate for a given gasifier design, so by varying the gasification rate the ratio of water to coal gasified can be modified to improve the product gas quality or, alternatively, the gasifier design can be modified to change the water flow rate. In this study, the water rate was estimated based on an approximate understanding of the site characteristics and the results of the groundwater flow study suggest that the performance of the site could be improved. This requires an iterative approach to site design that requires considerable computational resources and time. It should be noted that even the better of the two gases was approximately 20% lower in calorific value than the best reported experimental UCG product gas, based on conservative performance estimates, so there is some potential for improvement.

The higher hydrocarbons removed from the product gas were taken as a revenue neutral by-product, as the exact quantity and quality of these can not be established without experimental study. There are a number of options for these that could affect the plant operations and economic performance. The simplest option is sale as a feedstock for chemical or fuel manufacture, although there are some concerns regarding the quality and the effects of ageing on the usefulness of these types of material. Another option is to reform the material using high temperatures, which will produce another fuel gas stream. This has some merit, as it can be used to stabilise the fuel gas flow and quality, possibly improving the characteristics of the gas as feed to the gas turbine. A variant of this is to reinject the hydrocarbons into the high temperature region of the UCG reactor, but this would require careful examination to ensure that environmental risk is minimal. An alternative disposal method would be to use the hydrocarbons as a fuel for supplementary steam generation in a boiler, which would add to electricity generation from the steam cycle of the power plant. These options can only be examined fully when an accurate estimate of the quantities generated from the site and the chemical characteristics can be made.

8.3 Groundwater and subsidence

The analysis of groundwater changes and subsidence caused by the UCG development was analysed in two parts, the first looking at the local groundwater availability impacts and subsidence and the second looking at the regional impact on groundwater availability and the potential spread of contaminants from the site. Some tuning of the modelling process is required and, as modelled, the clean-up phase of the process extracted far more water than was necessary. The cleanup was specified as a two year phase, based on the experience at the Chinchilla UCG site, but the deeper site and different gasifier design used in this study resulted in faster cleaning of the affected area by returning water flow. The way this was specified in the models was inadequate and the water removal was far greater than has been required in past UCG trials.

The quantitative output from the modelling suggests that the impact on water availability in the area will be noticeable, but not excessive, and groundwater levels will recover to normal within several years of operations ceasing. To put the UCG development in the context of other resource utilisation technologies, it is expected that the UCG process would extract less water than an underground mine of similar size or a coal seam methane extraction operation at the same site. This is because the UCG reactor is pressurised during operation, so there is less driving force for water flow into the reactor than there is for depressurised longwall mines or dewatered coal seam methane sites. It should also be noted that the UCG site would be much smaller in scale than typical installations of the other technologies, so will be substantially lower impact. It is not anticipated that power generation would exceed the proposed 400MWe at a single site. There are also differences in the way the water is removed in UCG, as water condensed from the product gas will have been distilled and therefore will have lower salt content than water that has been pumped out, but will also contain organics that require separation before the water is suitable for other uses, potentially agricultural. This will be a different process to the treatment of water that is pumped out during mining or coal seam methane, which is typically left to evaporate as it is too saline for other uses. Some water will be pumped from the UCG site during operation for control purposes and during the cleanup process, but this will be a significantly smaller volume than the water condensed out of the product gas.
The evaluation of the potential for groundwater contamination was approached by looking at the impact of concentrating the salts in the cavity due to evaporation of the water during operations to leave a more concentrated saline solution after cleanup, and the impact of having a constant source of organic contamination after cleanup due to residual higher hydrocarbon deposits. These were examined separately and in both cases assume that the cleanup is ineffectual, simply a single flush of the cavity. In reality, it is expected that the environmental regulators would require that the cleanup be continued until contaminant concentrations are reduced to negligible levels. Concentrating the salts in the cavity has only a minor short-term impact at the site, as it is rapidly dispersed by water flowing through the subject area and the groundwater is fairly saline naturally. The organic contaminant of interest, based on past trial results, was benzene and this was assumed to leak from non-aqueous phase deposits in the cavity at a constant rate indefinitely. The spread of benzene from the cavity is slow, but it is predicted to flow not only in the coal seam, but also into the overlying Springbok Formation due to the collapse of overburden into the cavity resulting in linking of the aquifers. With no oxidation, adsorption or decay in release rate for the benzene there would be a steady spread of contamination from the affected volume. This is a fairly self-evident result given the input assumptions to the model, but should be carefully considered to determine the importance of the predictions. The slow spread of contaminant has contrasting impacts; it gives time for a renewed cleanup operation to remove the source of the contaminants, but it also means that monitoring wells have to be placed close to the affected volume to detect problems quickly after the initial cleanup process is complete. Further experimental data on the leaching of soluble organics from non-aqueous phase deposits is required to improve the models, as it is obvious that there will not be a constant rate indefinitely. It is also likely that significant quantities will be removed from the water by reaction and adsorption, which will constrain the area of significant contamination. The level of contamination predicted in the overlying aquifer is quite minor, given that this is not drinking water. In reality, contamination of this type is difficult to predict as it is dependent on the efficiency of cleanup and there are very few previous UCG trials that have attempted this type of cleaning. The Rocky Mountain 1 trial and cleanup used similar techniques and avoided contamination. Also, the Lin Energy trial at Chinchilla used a similar cleanup approach and published results show no contamination, but public access to details of the testing process has been blocked due to commercial confidentiality.

Subsidence was also examined and was a key input into the groundwater modelling, as it results in disruption of strata that can lead to increased permeability and interconnection of aquifers. Surface subsidence due to UCG is predicted to be relatively minor, with the maximum value being less than 0.5m. This would have negligible impact on the existing land use in the region, mostly grazing, after UCG operations have ceased. UCG operations under buildings and waterways should be avoided. If necessary, the subsidence could be reduced by using alternative UCG designs with narrow cavities and this would be advised for shallower coal seams or sensitive sites.

8.4 Social and legislative contexts

The social issues that are likely to affect a prospective UCG project were examined in three workshops involving experts, city dwellers or country people. There were some differences in the benefits and concerns as viewed by the different groups, with more emphasis on local impacts from country people that are likely to be near a development. Environment, safety, economics and trust in the operators were noted as key areas of interest. Surprisingly, there was no direct mention of Greenhouse emissions and groundwater was not a primary concern of the members of the public involved. This contrasts to a UK study of public attitudes that suggested that UCG would only be acceptable in combination with carbon dioxide sequestration. A process such as UCG makes an interesting case study in this type of public dialogue, as there is very little knowledge of the process in the general public. Therefore, all information on the process would have to be supplied into the dialogue and the outcomes would be relatively independent of external influences.

Legislation that impacts on UCG operations is quite scarce and it would be expected that a commercial site would have environmental requirements set by negotiation with the regulatory authorities. This is a challenge when evaluating the environmental performance of the process and most of the predictions of performance in this study can not be definitely compared to set limits. For example, a key concern
regards groundwater contamination, but there are no specific limits for the materials that are likely to be released. Therefore, most findings of this study can be regarded as qualitative and represent an expectation that the results will, or will not, be acceptable based on reasonable limits being set by regulators. This is an important issue and is difficult to resolve without having a genuine proposal for a UCG operation that can be discussed with government authorities. The Queensland government has stated that regulations will be published for UCG operations in the future, but has not commenced the public review of the proposed regulations yet.

8.5 Conclusions

The environmental barriers to implementation of UCG have been examined, specifically regarding Greenhouse emissions, groundwater impacts, subsidence, social issues and legislative requirements. The study was performed based around a scenario of a nominal 400MWe electricity generation plant based on UCG in the eastern Surat Basin in Queensland. This scenario represents a full-scale commercial development that would require a full environmental impact assessment prior to approval, so is a realistic size of development that can be compared to other resource utilisation and power generation projects. The study attempted to analyse realistic design, operation and cleanup of the site, although the cleanup was deliberately modelled as ineffectual to allow a representation of the spread of contaminants as a worst case scenario. In some aspects of the study there was inclusion of variants to examine the impact of operational and design changes on performance.

The predictions from the process simulation study suggested that UCG could provide a cost effective method of reducing Greenhouse gas emissions in conjunction with carbon dioxide removal for sequestration with substantial cost savings in comparison with surface gasification. Other process studies were less promising, either because of minimal reduction in Greenhouse emissions or high electricity costs due to the additional plant requirements. Groundwater use and subsidence due to UCG operations do not appear to be excessive and are unlikely to have a significant impact on current land use in the region, which could be returned to normal within a few years of UCG operations ceasing. If cleanup is ineffectual groundwater contamination could occur, however it will be slow spreading and could be detected if a suitable monitoring system is used after site shutdown. Dilution is likely to reduce concentrations to relatively insignificant levels if the aquifer is not close to the coal seam and is not used as drinking water. It is difficult to predict the likelihood of this occurring as it requires assumptions regarding performance of the site cleanup phase and properties of the materials left in the site. The preliminary study of social issues did not reveal any specific issues of the technology that might cause hindrance to implementation of UCG in Australia. However, it is evident that care must be taken in public dialogue if an experimental UCG site is to be commissioned, as there is a generally poor understanding of the process and its implications. The legislative requirements of the technology are also poorly defined and, while it is not expected that the technology will breach any current legislation, it is likely that the requirements for a commercial development would be negotiated with the regulatory authorities rather than being reliant on existing regulations.
9 RECOMMENDATIONS FOR FUTURE WORK

In the course of this study there have been some specific areas exposed where there is insufficient data available to accurately predict the behaviour of the UCG process as designed. One of the key areas has been the formation of tars during operation, the composition and quantity of these and their behaviour during and after cleanup. There is no published data on the formation of tars in this type of operation and it is likely that the characteristics will be strongly influenced by the coal and operating conditions. Lack of this data interferes with a number of aspects of the study, ranging from process options to contaminant generation. It is expected that an experimental study would be required to firstly generate tars and then examine their breakdown in water.

Other issues that could be the subject of further research include:

- A more detailed analysis of the regional hydrology, which is critical to the determination of water flow for both UCG and coal seam methane operations in the region.
- Enhancement to the geotechnical model to allow local prediction of contaminant movements and the influence of thermal effects on roof materials.
- Alternative uses for the product gas, in particular methods to avoid the performance issues involved in the use of currently available gas turbines with low carbon gases.
- A risk assessment framework for evaluating the viability of UCG based processes.
10 REFERENCES


CISS (2001) *Coal in a Sustainable Society*, ACARP Report C9058, Supplementary Appendix X.


Environment Australia (2001) *Environment Australia: Guidelines for Triple Bottom Line reporting*


APPENDIX A : UCG BACKGROUND MATERIAL

Summary

Underground coal gasification (UCG) is by no means a recent or untested technology, however it has never been applied commercially in the Western world. Large-scale facilities have been in use in countries of the former Soviet Union for over 40 years, mostly for the generation of fuel gas to be used in boilers for power generation. More recently sites in China have been used for hydrogen production, supply of town gas and ammonia synthesis. Reportedly a large site has also been commissioned in North Korea for the supply of fuel gas. In addition, numerous tests have been conducted worldwide with significant testing programs in the USA during the 1970s and 1980s, and Western Europe in the 1980s and 1990s. In total, over 15 million tonnes of coal have been gasified by the technique and this has been comprised of coal of all ranks, depths ranging from 10 to 1200 m underground and seam thicknesses of between 0.3 and 30 metres, mostly near horizontal but some steeply angled. Oxidant gases have ranged from air through various oxygen enrichments to 95% oxygen and a variety of different techniques of piping arrangement have been tested.

The main stumbling block to more widespread commercialisation of UCG has been the number of operational problems that have occurred during trials in the USA and Western Europe. While these have been varied in nature, they almost invariably relate back to a poor understanding of the ground conditions at the sites. Besides a few technical issues relating to equipment selection and maintenance, there have been no major difficulties with the techniques available or in specifying suitable materials for use in the process. It appears that the major issue is in correctly defining the geological characteristics and layout of the site before commencing the process design and operation. Key characteristics in selection of a good gasification site include:

- Seam of 10 metre or more thickness
- Between 300 to 400 metres below ground level
- Site with a high hydraulic head
- Minimal faulting of the seam
- Ash content of coal less than 40% (ad basis)
- Low permeability in the surrounding rock
- Structurally sound overburden
- No good water aquifers in the vicinity of the coal seam

Coal quality is only a minor issue. There is no significant influence of rank on the process performance excepting the potential for problems arising from high moisture contents in very low rank coals and the poor ignition properties of very high rank coals. There is some sensitivity to the dip of the coal seam, with most gasification techniques suited to seams with dip less than 20°. Different techniques can be used on steeply dipping coal beds with slope over 50°.

The major risk arising from UCG processes is large-scale failure of the strata directly overlying the coal seam. This can have two significant impacts: firstly, complete failure of the process due to blockages and redirection of gas flows and, secondly, contamination of overlying aquifers with process by-products and coal organics. The importance of the latter impact will depend on the quality of the aquifer water and the extent of contaminant spread.

Environmental risks associated with UCG are largely associated with potential contamination of good quality groundwater. This can arise when subsidence of overburden into the gasification cavity results in disruption of aquifer systems, potentially bringing good quality water flows into contact with heavily contaminated waters around the coal seam. Lesser risk is associated with subsidence effects on the surface, which are similar to those expected when other coal extraction techniques are used. Contaminated water processing at the surface installations would have similar environmental restrictions to related industries, such as petrochemical processing. Surface impact of equipment will be minimal and transient for the actual gasification field, however the gas processing and utilisation plant will be relatively permanent installations typically located adjacent to the field.
Product gas quality from UCG is comparable in calorific value to that of surface gasifiers but is different in composition, typically containing higher concentrations of methane and carbon dioxide to offset a lower concentration of carbon monoxide. As is typical with other processes producing these types of gas, it should be used at site with minimal piping distances for economic and safety reasons. The overall recovery of coal from a gasification field would be expected to be in the range 80-90%, depending on the structural requirements for retaining pillars. Of the coal gasified, the cold gas efficiency (recovery of coal energy in the gas) should exceed 75% for an oxygen-blown process, or up to 65% for an air-blown process.

Control of the gasification process is an important issue. There is limited ability to adjust the progress of gasification and the product gas quality. In part this will be countered through the use of multiple gasifiers in a large-scale gasification field. However, a more detailed understanding of the behaviour of UCG and formulation of techniques for optimising performance would improve the future prospects of the process.

Costing of the process is poorly defined due to the lack of case study data, however indicative economic analysis suggests that the product gas will have a cost between that of mined coal and natural gas. The cost of product gas from a suitable site is expected to fall in the range of $2.00-2.50 per GJ in a medium calorific value form, approximately one quarter of the calorific value of natural gas. This would make the generation of electricity uneconomic under Australian conditions but may be viable in other countries. Alternative uses of the gas, in particular synthesis of liquid fuels, are likely economically viable due to the higher value of the end product. Further examination of the economics of processes to convert the gas into various liquids would be required to verify this.

This appendix covers:
- A review of prior experience of UCG worldwide
- An examination of the effects of ground conditions on UCG operations
- Established environmental risks from UCG
- Methods for controlling UCG sites

Prior Experience in underground coal gasification

Activities worldwide
Considering the lack of commercial operations in Western countries, there have been a surprising number of trials of underground coal gasification worldwide. In excess of 50 trials, mostly in the former USSR and the USA, have been performed and many of these have been comprised of tests of more than one type of technique during the trial. Admittedly, many of the trials have been relatively small, gasifying only small amounts of coal over a short period of time. Some characteristics of these trials are given in the table below, with the data being limited for many of the trials due to a lack of publications. In total, in excess of 15 million tonnes of coal have been gasified, with over 4 million tonnes of this being at two gasification sites in the former Soviet Union, Yuzhno-Abinsk and Angren. A summary of the locations shown in Figure A.1 and brief information on the most sites is given in Table A.1.
Of all the UCG sites used, there has only been constructive use of the product gas at several Soviet sites and one each in China and North Korea. The Soviet sites currently operate intermittently, largely depending on the availability of natural gas, with the product gas being used as fuel in power station boilers. Minimal information is available on the North Korean installation, however it also appears to be for generation of low quality fuel gas for boilers, probably using Soviet techniques. The Chinese site is used to generate a product gas with a high concentration of hydrogen that is purified using pressure swing adsorption.

The closest approach to a commercial application of technology in the Western world has been two attempts at commissioning a plant at the Rawlins test site in Wyoming, USA. Following good test results at the site, it was intended to install a full commercial facility producing ammonia and then fertiliser from the product gas. The first attempt was made in the late 1980s and was abandoned when natural gas prices fell in the USA, making the plant economics marginal. The proposal was revived in 1994, and a test performed in 1995. This resulted in groundwater contamination that required extensive remediation work and the project was abandoned. It appears that the contamination was a result of drilling errors that led the operators to exceed the maximum permitted pressure for an extended period during start-up.

In Australia, underground coal gasification was studied as a method of utilising coal in the Leigh Creek area of South Australia and advice given that the method would be economically viable for power generation\textsuperscript{28}. However, no underground gasification activities occurred. The sole gasification trials of any note in Australia have been the activities of Linc Energy, who have been running a demonstration site near Chinchilla (Queensland) since late 1999. The technique used is the standard Soviet approach of vertically drilled holes, spaced between 20 and 50 metres apart, with compressed air injected in one hole and product gas taken from the other. The coal seam being used is approximately 130 metres below ground level and between 8 and 10 metres thick. The product gas produced is of low calorific value (~5.0 MJ/m\(^3\)), but can be used as fuel in a gas turbine for electricity generation. No operational difficulties have been reported at the site and monitoring of water quality in aquifers surrounding the site has not detected any contamination.

The tables on the following pages give a summary of results for most underground coal gasification trials. Unfortunately there is little published data on the smaller trials, often run by commercial interests wishing...
to examine the feasibility of gasification techniques. The major sets of data are for the Soviet trials, including the full commercial scale operations, the US DOE sponsored trials and the more recent European trials. Other data is presented where it is available but in some cases this may be inaccurate or unrepresentative of the full results of the trial. In many cases the data in the tables is approximate.

Table A.1: Summary of past UCG experiments

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<th>Test</th>
<th>Year</th>
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<th>Seam depth m</th>
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<td>SubbitC</td>
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Key to abbreviations:
- Chamber – Mined tunnels around a explosively fractured block of coal
- Stream – Gas flows across a reacting coal face
- Single V – Product is taken out same well as reactant
- VW – Vertical wells
- SDB – Steeply Dipping Bed
- CRIP – Controlled Retracting Injection Point
- Tunnel – Mined tunnels delineate UCG reactor (some similarity to the chamber method)

Comments on data in table:
- The data on the tests is as published and may not always be representative of normal site operations. In particular, some of the Soviet sites operated for extremely long times under a range of conditions and the data shown is a snapshot of one or more sets of operating parameters.
- Naming of the tests was often on an ad-hoc basis, so in some cases different researchers have given different titles to the same test. Where it was possible to determine that this had occurred, the results were combined in the table and the different test names are given. For some of the
Soviet tests the name has been translated into more than one different spelling, with the most common being given in the table.

**Techniques**

A number of different gasification techniques have been developed to allow economic gasification of coal in different situations. Any of these techniques can be used with either air or oxygen as the oxidant gas, however some have obvious advantages with one or the other gas. Simplistically, the gasification procedure requires an injection hole and a production hole with a region of permeable coal between them. The two major techniques that are used for roughly horizontal coal seams are vertical wells, commonly used by the Soviets, and the controlled retracting injection point (CRIP) approach, that has been used in the USA, Belgium and Spain. A different technique is used for sloping coal beds, used in both Soviet and USA trials. A mined tunnel approach has been used in the UK, early Soviet work and China. Specific notes for each technique are given with diagrammatic representations on the following pages.

The techniques that are most likely to be applied to near-horizontal coal seams at a Greenfield site are either the vertical wells or some variation of the CRIP approach. For a steeply dipping seam a combination of vertical and angled in-seam holes would typically be used, a hybrid approach taking advantage of the ease with which in-seam drilling can be applied to the angled seams.

The vertical wells approach is relatively simple in operation, a number of holes are drilled and cased at regular intervals and linked by any number of methods, most commonly by burning a path between the holes but more greatly spaced holes could be linked by drilling using a down hole drill. Ignition of the coal is typically commenced by injection of a spontaneously combusting material, possibly with addition of a supplementary liquid fuel. Gasification proceeds by injection of oxidant gas into one row of holes and product gas is extracted from a parallel row of holes. When oxygen is detected in the product gas a new row of holes is commissioned to expose new coal to gasification.

The CRIP technique uses a long, directionally drilled, in-seam injection pipe and a vertical product pipe. The injection pipe will be as long as the drilling technology available will allow, currently approximately 1.5 km underground. By locating the ends of the production and injection pipe in close proximity, it is relatively easy to obtain flow between the two holes and ignite the coal. With progress of gasification, the injection pipe is shortened by burning through a section close to the void, performed by inserting a burner or injecting flammable material to increase the temperature at the pipe exit. In this way the gasification void can be expanded until all the coal alongside the injection pipe has been gasified.

A variation of the CRIP technique, that has not been tested but is expected to give improved performance, is the ‘Knife-edge’ CRIP. This involves inserting two parallel, directionally drilled, in-seam pipes and igniting the coal between the pipe ends. The injection well is retracted with progress of gasification. The intent of this method is to keep a reacting coalface between the two pipes that stays at constant size throughout gasification of the coal between the two pipes. This simplifies control over the gasification procedure as all other techniques result in a changing reaction area with time. It is expected that the CRIP can be made self-retracting through selection of grades of steel such that the pipes that will melt when in contact with the burning coalface.

The economics and practicality of the CRIP techniques are sensitive to the oxidant gas used due to the different gas volumes that must be injected. When using air, there is a slight energy dilution effect in the gasification due to the extra quantity of gas that must be heated. This means that more oxygen must be added, in the form of air, to maintain the reactions. This is important for the CRIP because of the restriction on casing sizes that can be used in directional drilling over long distances. When using greater than 90% oxygen as the oxidant, the injection pipe size required would be approximately 100-150 mm, in order to keep gas velocities and pressure drop to reasonable level. This is for a seam at approximately 300 m depth, as the sizing varies with the gas pressure used. Experience in directional drilling is mostly in the size range of 100 mm casing, which is used in coal bed methane extraction, however there is not technical restraint, other than larger capacity equipment, up to 200 mm casing. Above this there is greater
uncertainty in the capabilities of drilling contractors, and rapidly escalating costs. This leads to both technical and economic pressure on using smaller pipes in the CRIP, and this therefore leads to the utilisation of oxygen, rather than air, in the gasification process.

Vertical well gasification layouts are less sensitive to the oxidant type due to lesser technical and economic pressures on the piping sizes. The selection of oxidant will therefore be on the basis of performance during gasification. Using oxygen is preferable for many applications as it reduces the concentration of inert gases in the product stream and, due to the reduced energy dilution in the process, the ratio of carbon dioxide to useful gases is reduced. The product gas therefore has a much higher calorific value and higher proportion of potentially useful gases, such as hydrogen, carbon monoxide and methane. Of course, the production of oxygen for use in the gasification process has a cost and on the simple economics of cost per unit energy in the product gas, the use of air is favourable due to the lower capital and operating costs. This is partly due to the underground gasification process being an efficient extractor of coal bed methane and coal volatiles, regardless of the oxidant gas used, so the product gas has a higher calorific value than is expected from the gasification reactions.

Other feeds are sometimes used in gasification trials, notably steam and water. Addition of these would suggest that there was insufficient moisture surrounding the coal seam. As most coal seams acts as aquifers, it suggests that those trials were using excessive operating pressure that was keeping water out of the gasification void or the water supply was exhausted due to a low replenishment rate from surrounding rock.
(a) **Vertical wells:**

**Notes:**
- This is the typical technique used by the Soviets and early trials in the USA. It involves drilling holes in parallel rows and progressively advancing the gasification process through the rows to consume the coal in a block. Variations in the selection of product and feedholes can be used to adapt to changes in the gasifier void, sometimes caused by blockages due to roof collapse or variability in reaction rates between different parts of the block.
- Common Soviet practice included angling the pipes to avoid damage during subsidence and recovery of the casing after an area was exhausted to allow subsequent reuse.
- This technique is best suited to clear level landscape with relatively shallow coal seams (<300m).
- Linking between each row of holes and adjacent holes is typically carried out in advance of production, with the most common method being termed “reverse combustion”, where ignition is at a product hole and the flame front progresses towards the injection hole where air is being injected. Once the path between the two holes is enlarged enough for free gas flow, the airflow rate is reduced and gasification proceeds.
- Typically, the spacing between holes is in the range of 20 to 30m, however the Linc Energy test using this technique has reportedly used distances of up to 50m without difficulties (this will be dependent on coal permeability and moisture content).
(b) **Steeply Dipping Bed (SDB) technique**

**Notes:**

- This technique was tested by both the Soviets and the USA. It is relatively simple but relies on specific site constraints.
- A coal seam at a steep angle to the horizontal (typically greater than 30°) has a vertical feed and an angled product pipe inserted. The feed pipe should exit at lower than half way up the seam and the product pipe should be in the upper part of the seam.
- After ignition, a cavity will form and grow until the feed gas progresses into the product pipe without reaction. Two approaches can then be used, namely, a new feed pipe can be inserted further down the seam or the product pipe can be withdrawn up the seam. Either approach will lead to expansion of the gasifier void if the flow path doesn’t become blocked with residue from the coal or collapsing material from the roof.
- Disadvantages to this technique are the specific site characteristics required (this limits the amount of coal that is accessible), also the drilling distances can become excessive as the seam dips further and the operating pressures required vary with the coal depth. There is also some tendency for the feed pipe to become clogged due to deposition of material from the coal consumed above it.
- An advantage of the technique is the ease of forming links between the pipes, due to the tendency of the void to grow upwards towards the product pipe.
(c) *Standard Controlled Retracting Injection Point (CRIP) technique*

**Notes:**

- This technique is the current ‘cutting edge’ UCG technology, as tested in the most recent trials in the USA (1980s) and western European trials in Spain and Belgium (1980s & 1990s).
- The injection pipe is inserted into the coal seam through directional, in-seam drilling.
- Current technology allows for the pipe to run for distances up to 1 kilometre horizontally in the coal seam, although it is preferably to limit the casing size to below 150 mm.
- Best practice is to have the injection pipe in the bottom third of the coal seam at all times.
- Initially the injection pipe will almost reach the vertical production pipe, so that a flow path for gases can be created and the coal ignited.
- As gas flow improves, oxygen will carry into the production pipe and the injection pipe will be retracted. There are two alternate methods for this:
  - Using a burner inserted into the injection pipe to destroy a section of the pipe and thereby create a new injection point (as used in previous trials); or
  - Melt the pipe by causing greater combustion activity in the surrounding coal. This requires careful selection of the grade of steel used in the injection pipe casing and a temporary increase in oxygen flow to the gasifier.
- Directional drilling techniques have improved dramatically, however there is some concern that the cost would be higher than for a standard vertical well technique. This would depend largely on the depth of the coal seam, with greater than 300m appearing to favour CRIP. There is also a greater risk of failure using the CRIP as the drilling technique is more difficult and there is more reliance on a single pipe not failing (casing failure is a fairly common fault during UCG tests).
- The limit on size of the piping used during directional drilling makes oxygen injection preferable to air, as the reduced volume results in lower gas velocity and pressure drop.
(d) *Knife-edge CRIP*

Notes:
- Successfully used in the Rocky Mountain 1 trial (1987-88) with relatively short wells approximately 180m in-seam and not parallel.
- Two directionally drilled wells extending up to 1 kilometre horizontally in the coal seam, initially coming close together at the end to assist in ignition and establishing gasification but with the majority of the pipe parallel at a spacing of approximately 20-30 metres (possibly greater if conditions allow).
- Injection into one pipe and production from the other.
- The injection point is retracted, either continuously through thermal destruction of the pipe with reaction of the surrounding coal or via an inserted burner that can be used to destroy pipe sections. The production well is not cased or cased with easily destroyed material.
- Advantages of this techniques over conventional CRIP are in enhanced control over the size and progress of the reaction front through the coal, essentially the reacting coal will be the area between the ends of the two pipes and will remain approximately constant in size with reaction.
- Disadvantages of this technique are in the greater length of directional drilling required, which carries a higher cost and greater risk of deviation from the coal seam.
- There may be limitations on gasification rates due to the volume increase in product gas compared to injected gas and the restriction on pipe sizes in directional drilling.
Notes:

- This technique, used by the Chinese in recent years, is not widely discussed in literature. It is termed “long tunnel, large section and two stage” (LLTS) by the Chinese. It has some similarities to earlier British and Soviet approaches.
- Currently about 12 sites in China use this technique, with various minor differences in design, and it is in commercial use, but on a very small-scale.
- A typical new site would have 2m tunnels mined around three sides of a rectangle about 200-300m long per side. Wells to the surface of about 1.5m internal diameter can be used to access the tunnels and act as injection and production wells. The sites are typically designed to provide 5 years of operation and at least two gasifiers will be constructed.
- Gasification can be performed in two stages with two distinctly different product gas mixtures. The first stage is essentially combustion of the coal with air, producing a large zone of high temperature char. The gasifier is then evacuated to remove the first stage product gases and the hot zone is gasified using steam until it has cooled below sustainable reaction temperatures.
- Product gas from the first stage is essentially of the same composition as boiler flue gas, possibly with higher carbon monoxide content, and can be used as supplementary feed to a boiler for heat recovery. Product gas from the second stage has high hydrogen content (>50% in small trials but lower in full production), and can be processed via pressure swing adsorption to produce a hydrogen gas product.
- Overall, the efficiency of the process appears to be fairly poor. The product from the second stage of the process is typically reported, ignoring the long periods with poor gas quality during the first stage.
- Some sites blend the two gases from adjacent gasifiers in different stages of operation to produce a synthesis gas of suitable carbon monoxide to hydrogen ratio, with surplus gas from one stream flared or used as fuel.
- Other sites operate only on air for the production of town gas and this appears to have been satisfactory with a high volatile bituminous coals that produce high quantities of methane if partially combusted.
Product gas quality
Gas quality from UCG sites varies considerably due to factors such as the coal type, moisture entering the reaction zone, heat losses to the surrounding rock, coal depth and the feed gases used. Data from a range of experimental trials is shown in terms of product gas composition in Figure A.2 and as the calorific value of the product gas as a function of coal seam depth in Figure A.3 and coal seam thickness in Figure A.4, with distinction made between the use of different oxidant gases in the gasifiers. A selection of results from surface gasifiers is also included. Gas compositions from a selection of underground test results and some modern surface gasifiers are given in Table A.2. All data for UCG tests are as reported by the researchers and can be spot values or averages over periods of stable operation.

Typically, the product gas from UCG has higher methane content than the product from the various surface gasifiers. This is offset by a lower carbon monoxide content, giving a similar calorific value. The higher methane content can be due to several causes, either it is a result of reaction of hydrogen with carbon, extraction of coal bed methane or thermal breakdown of coal. The lower temperatures involved in UCG are likely to encourage methane formation during reaction, particularly at high pressures, and also pyrolysis reactions which lead to higher release of hydrocarbons from coal, rather than carbon monoxide and hydrogen. The gas composition is also unlikely to adjust to equilibrium at lower temperatures, so any released methane will not convert to other gases, as is the case in high temperature processes. The presence of larger concentrations of methane would typically be an advantage in power generation or natural gas synthesis operations, but can be disadvantageous in synthesis reactions.

The temperature and pressure of the product gas from different tests can vary markedly. The pressure is largely dependent on the hydrostatic pressure at the gasifier depth, with adjustment for pressure drops in the piping. The temperature of the product gas is extremely variable and depends on factors such as the product pipe length, gas flow rate and the ground conditions. Typically it is in the range 200-800°C and if at higher temperatures quenching through water injection or water-jacketing the pipe will be used to reduce the risk of pipe failure. These measures can assist in recovery of energy from the product gas for use in other parts of an attached process. Soviet tests have found that using waste heat from the product gas to generate steam for injection into the gasifier can improve operation efficiency by approximately 10%.

Figure A.2: Product gas compositions from various gasification processes
Figure A.3: Product gas calorific value relative to coal seam depth

Figure A.4: Product gas calorific value relative to coal seam thickness
Table A.2: Product gas quality for selected underground and surface coal gasifiers

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<th>CO %vol, dry</th>
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<th>CH₄ %vol, dry</th>
<th>CO₂ %vol, dry</th>
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**Efficiency of UCG**

The efficiency of UCG has been determined using several different criteria, namely the proportion of generated gas recovered, the fraction of coal consumed within the bounds of the operation and the overall energy efficiency on the basis of gas calorific value relative to coal energy. Unfortunately all these measures are subject to inaccuracies in the assumptions required during calculation. A key factor in all of the calculations is the mass of coal affected during gasification and this cannot be accurately determined without excavation of the site after gasification. This is a lesser issue for the large Soviet sites, as they are typically laid out in a rectangular configuration and exhausted before closure. However the smaller scale tests will result in an irregularly shaped cavity, the size of which cannot be accurately estimated. Excavation of the Centralia/Tono site led to the conclusion that the estimate of the quantity of coal gasified had been in error by approximately 20%. The following efficiency estimates are therefore the best estimates of researchers but may be subject to significant error.

The recovery figures have been estimated for many Soviet and USA trials, occasionally being calculated to exceed 100%, indicating errors in the site mass balance. As a general figure the gas recovery appears to average around 90%, but in some cases it is uncertain where the remaining 10% goes. In the shallow Soviet tests, it has been noted that the water table at the site can drop significantly, thereby exposing the top part of the gasifier to dry rock and allowing leakage of gas into the rock strata. Also, in some tests in the USA it was noted that at high operating pressures gas leakage increased due to the gas being forced into surrounding rock. Large-scale roof collapse has a similar affect as it exposes strata with lower hydrostatic pressure to the higher-pressure gas void. In normal operating situations, where the void is a bubble in wet coal and rock, the loss of gas would be caused by various gas components dissolving into the surrounding water. Some components, specifically carbon dioxide, will do this significantly at high pressures. However the desired product gases, namely hydrogen, carbon monoxide and methane, will dissolve to a lesser extent. It is unlikely, therefore, that the leakage will be significant where the gasifier is correctly operated.

Where sites have been excavated, the recovery of coal from the site has been typically in the range of 70 to 90 percent for the Soviet sites, with the values tending to increase as the technology matured. For trials
in the USA, estimates in the range of 85 to 90 percent coal recovery have been stated in the literature. However, these figures may not be representative of large-scale operations.

The proportion of energy recovered in gas form compared to the energy content of the affected coal can only be determined approximately. Examples of the energy flows relative to the energy in the coal gasified are given in Figure A.5. The air-blown data is for the Angren site, an air-blown gasification site using the vertical wells technique, and the oxygen-blown data is for the Rocky Mountain test using the CRIP technique. The oxygen-blown techniques typically have a higher recovery of energy in a usable form, in this case a cold gas efficiency of 76% which is similar to that for oxygen-blown surface gasifiers. Underground energy losses are higher for air-blown processes and the product gas quality is significantly lower, in this case yielding a cold gas efficiency of only 52% but other sites have been as high as 65%. For both cases, the char that was left in the gasifier was excluded, which leads to the figures being inflated by approximately 10%. The exclusion of the char is on the basis that it has not been extracted, so correlates with mining losses rather than energy losses in the process.

![Figure A.5: Energy flows in UCG processes: 1. Angren & 2. Rocky Mountain](image)

**Effects of ground conditions on UCG operations**

**Introduction**

Underground coal gasification will be affected by a number of different factors concerning the site selected. Almost every operational parameter will be influenced by the simplistic characteristics of coal seam thickness, depth and angle. In addition, the coal characteristics, such as ash and volatile contents, and geological factors, such as the permeability and thermal properties of coal and surrounding rock, will influence the rate of gasification, cavity shape and roof collapse. Unfortunately, it is difficult to do a systematic analysis of the impacts of all these parameters on the efficiency of UCG as it requires a large number of tests at a large number of sites. The only set of results that comes close to examining all parameters is that from the early Soviet tests. These aimed to prove the concept of UCG as a method for recovery of any coal from any site, so tests were performed on a diverse range of coals in seams of different thickness and depth. It was essentially proven that the techniques they had developed could gasify these seams, however the efficiency of the process was clearly affected by the rate of water ingress into the void and the coal seam thickness. This mostly relates to the wastage of heat in the gasification void. For example, the water must be vaporised and a thin seam has a higher surface area for heat loss per unit of coal. Consideration of some of these and other influences is given below.

**Coal characteristics**

Coal characteristics that are expected to influence gasification behaviour include rank, swelling, and ash, moisture, volatile matter and methane contents. Coal of every rank from lignite to anthracite has been gasified experimentally, with no evidence of significant rank effects. This is likely to be due to masking of rank effects by more significant factors, notably moisture tends to be inversely related to rank in lower rank coals. Similarly, there has been no evidence of coal swelling properties causing performance variability. Early researchers in the USA expected highly swelling coals to be difficult to gasify due to
potential blocking of gas flow paths in the early stages of gasification. However Soviet and later USA trials experienced no extra difficulty when gasify highly swelling coals. It should be noted that swelling properties of coals differ markedly in real situations compared to the laboratory analysis conditions, with factors such as pressure, temperature and gas composition being important.

Ash and moisture in coal act as energy sinks, requiring an input of energy from the combustion processes in order to raise their temperature to the operating temperature of the gasification process. In effect this means that the gasification temperature will be reduced, for the same oxygen input, in high ash and moisture content coals and reaction will be slowed or possibly cease. Alternatively, more oxygen can be added to increase the temperature, but this results in poorer quality product gas containing a higher proportion of oxidised species. Soviet research from Podmoskovia/Tula site\textsuperscript{18} indicates that the ash content of the coal has a significant impact on the product gas quality, as shown in Figure A.6. There is no evident reason for a decline in performance at low ash content, so it is likely that the results simply indicate a plateau in performance below 40% ash content. Above 50% ash there is a marked decline in product gas quality. The direct effect of coal moisture on gasification cannot be readily gauged, as the effects of water ingressing from surrounding strata will be more significant. This is discussed in the seam characteristics.

The influences of coal volatile matter and coal bed methane content have not been accurately quantified. Qualitatively, high contents of either should assist the process, both in making ignition of the seam easier and improving product gas quality. The release of either is not directly dependant on oxygen addition, with coal bed methane being liberated with increased permeability of the steam and the volatiles being released on heating of the coal above 400°C (approximately). The yield of volatiles is increased in the presence of oxygen, water vapour and hydrogen and the product gases are simpler than in an inert atmosphere. It is therefore difficult to estimate the volatile yield in a UCG operation with the volatile matter determined during laboratory analysis.

\textbf{Figure A.6: Impact of coal ash content on product gas quality}\textsuperscript{18}

\textbf{Seam characteristics}

The depth, thickness, dip and degree of faulting of the coal seam are considerable influences on the site performance and economics. Dipping of the seam is of lesser importance but may influence the technique used for gasification if it is steep (>30°). Other factors that are of influence to gasification are the coal permeability and the potential rate of water influx into a cavity, either from surrounding coal or rock.
Depth, through close relationship to the hydrostatic pressure, will be the main criteria in determining the operating pressure of the gasifier and is a major component of the drilling cost. The operating pressure has an almost linear influence on product gas quality but this is largely offset by increases in gas losses, according to Soviet data\textsuperscript{18}. This leads to optimum coal seam depth being dependent on economics and the requirement that the seam has a sufficient head of water above it to maintain sealing with prolonged operation. Similar to surface gasification, it is predicted that a pressure of between 2 and 3 MPa will provide optimum gasification rates.

Seam thickness is the dominant economic factor, given reasonable operating depth, as it controls the amount of coal that can be extracted per length of drilling and the heat loss to surrounding material. Soviet research indicated that it was possible to gasify coal in as thin as 1 metre thick seams, however UCG only becomes economically viable where the seams exceed 8 metres in thickness. This thickness can be comprised of several overlying seams where the material between them will collapse during gasification of the lower seams. No practical maximum thickness has been identified, with seams of 20-30 m thickness used at some of the more successful sites.

Permeability of the coal has significance in determining the ease of linking the injection and production holes during the initial stages of gasification, which determines the allowable spacing of the holes. Various techniques have been tested to increase permeability for the ignition stage and these have developed to the stage where ignition can be almost guaranteed given reasonable site design. During gasifier operation, permeability of both the coal and surrounding rock influences the rate of water ingress into the void, which then influences gasification behaviour. Water ingress rates and seam thickness are linked as influences on product gas quality from UCG, as shown in Figure A.7. Optimum conditions occur when there are low water ingress rates and thick coal seams. While a trend of improving gas quality with thickness is observed, it is likely that there is a maximum thickness of coal above which no increase, or even a decrease, in performance occurs. However, seams of over 30 m thickness are extremely uncommon, so the limit is unlikely to be encountered.

![Figure A.7: Impact of seam thickness and water ingress on product gas quality](image)

Faulting of the coal seam has several possible influences on performance. Frequent faulting leads to a lack of seam continuity that can result in difficulties in designing gasification layouts for large sites. This lack of seam continuity can make the linkage of production and injection holes difficult or impossible. In
addition, the presence of faults can lead to either excessive water ingress into the void or escape of gas into the surrounding strata.

**Roof characteristics**
The strata overlying the coal seam have two effects on gasification. Firstly, they can provide water that will ingress into the gasification void and, secondly, they will collapse into the void when thermally damaged and insufficiently supported. Ideal roofing strata is of low porosity or permeability, so water ingress is minimal and gas escape unlikely, and will swell with heating with only minimal breakage at a slow rate\(^8\). Roofing material that is undesirable can be in varying forms. Material that is not significantly affected by heating and a lack of support can result in excessively large cavities, into which injected gases diffuse to the extent where they have negligible reaction with the coal or char. In contrast, large-scale roof collapse can result in blockage of injection and production pipes or even the gasifier void itself. Another possibility is that a zone of high permeability will occur in the overlying strata and gas flow will bypass the coal containing regions, leading to unreacted oxygen entering the production pipe. Excessive disruption of the overlying strata can also lead to disruption of aquifer systems, resulting in mixing of different quality water and possible contamination of clean groundwater bodies. Some materials, such as mudstone or siltstone, may fuse on heating to provide a stronger and less permeable overlying strata that would be beneficial to the process.

**Hydrology**
It is essential that coal seams used for UCG are below the water table and a large hydrostatic head should exist above the coal seam. Water is essential to operation of a gasifier as it provides the seal containing the gases. Where insufficient head of water exists above the gasifier, or low permeability in the aquifer prevents water movement, it is likely that long-term operations will dry the region above the gasifier and gas losses into these strata will become excessive. This is unlikely to occur except in gasification of shallow coal seams (\(<100\) m) or unusually low permeability situations. Excessively permeable strata in combination with high hydrostatic head is more likely and can lead to excessive water flow into the gasifier void, with resultant process poor performance.

The presence of clean waters close to the coal seam raises the issue of potential groundwater contamination. This can occur due to operational problems forcing pyrolysis products from the affected coal into aquifers, but is more likely to be a serious issue if aquifers are disrupted due to subsidence in the vicinity of gasifier void. This can lead to clean waters mixing with those directly in contact with heat-affected coal or possibly flowing through the coal. At sites where water is extracted for domestic or agricultural use from the vicinity of the coal seam, it is likely that the site would be deemed unsuitable for UCG by local authorities.

**Gasification site selection**
Some characteristics of a site that would be well suited for underground gasification become obvious from an analysis of the literature, consideration of the technical and environmental issues and a preliminary economic analysis. A general set of rules for site assessment is given in Table A.3, with both positive and negative site characteristics commented upon.
Table A.3: Key factors to examine when determining the site potential for UCG operations

<table>
<thead>
<tr>
<th>Item</th>
<th>Attribute</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>COAL CHARACTERISTICS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seam thickness</td>
<td>1m</td>
<td>Minimum feasible</td>
</tr>
<tr>
<td></td>
<td>10m+</td>
<td>Optimal</td>
</tr>
<tr>
<td>Rank</td>
<td>Low to high</td>
<td>Not significant other than very low rank coals tend to have high moisture and very high rank tend to be difficult to ignite</td>
</tr>
<tr>
<td>Ash</td>
<td>&lt;40% ad</td>
<td>Optimal</td>
</tr>
<tr>
<td></td>
<td>40-60% ad</td>
<td>Up to 30% drop in performance</td>
</tr>
<tr>
<td>Strength</td>
<td>Sheared &amp; weak</td>
<td>Can cause hole collapse and loss of drilling equipment</td>
</tr>
<tr>
<td><strong>GEOLOGY</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depth</td>
<td>200-400m</td>
<td>Best estimate as a trade-off between drilling economics, hydraulic head and gasification rates</td>
</tr>
<tr>
<td>Dip</td>
<td>0-20°</td>
<td>Optimal for most techniques</td>
</tr>
<tr>
<td></td>
<td>20-50°</td>
<td>Problematical</td>
</tr>
<tr>
<td></td>
<td>&gt;50%</td>
<td>Limited to SDB techniques</td>
</tr>
<tr>
<td>Structure</td>
<td>Minimal faulting</td>
<td>Need to know seam position accurately and CRIP technique requires continuous seam</td>
</tr>
<tr>
<td>Intrusions</td>
<td>Dips/sills</td>
<td>Problematical to coal continuity</td>
</tr>
<tr>
<td><strong>GEOTECHNICAL</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Immediate roof</td>
<td>Smooth &amp; even caving</td>
<td>For controlled collapse into cavity</td>
</tr>
<tr>
<td></td>
<td>Thermally stable</td>
<td>For controlled collapse into cavity</td>
</tr>
<tr>
<td></td>
<td>Minimal permeability</td>
<td>To minimise water flow into cavity</td>
</tr>
<tr>
<td>Overburden</td>
<td>Caving limited</td>
<td>Minimise surface effects and gas loss</td>
</tr>
<tr>
<td><strong>HYDROLOGY</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydraulic head</td>
<td>&gt;200m</td>
<td>Optimal for maintaining water seal</td>
</tr>
<tr>
<td>Aquifers</td>
<td>High permeability</td>
<td>Can flood cavity</td>
</tr>
<tr>
<td></td>
<td>Minimal permeability</td>
<td>Some water required for process</td>
</tr>
<tr>
<td></td>
<td>Good water</td>
<td>Pose a contamination risk</td>
</tr>
</tbody>
</table>

Selection of an ideal site for UCG activities is subjective, but can be estimated as having the following attributes:

- Coal seam of thickness 10 metres or more (good economics for coal recovery)
- No disruptions to seam continuity (simplifies layout and operation)
- Minimal dip in seam (dip has process pressure control ramifications)
- Depth of between 300 and 400m (good reaction pressure and drilling costs)
- High hydrostatic head (ensures good water seal around gasification cavity)
- Low permeability of overburden (minimal water flow into cavity)
- Ash content of the coal less than 40% (ad basis) (gas quality issue)
- Overburden unlikely to suffer major collapse under thermal and mechanical stress
- No good quality aquifers close to coal seam (contamination issue)
- Surface conditions suitable for low impact activities and some subsidence
Operational risks of UCG

A number of operational problems have resulted in poor performance or complete failure of UCG operations. This is not surprising considering the large number of tests performed, the large number of different site operators and the experimental nature of the techniques used. The most common problems are discussed below, with indications of the probability of occurrence and potential methods of avoiding these types of problems. The references are the same as used in developing the table in Appendix 1.

(a) Drilling problems

There are two different types of drilling problems that are likely to affect the establishment and operation of an UCG site. The first of these is inaccuracy in directing the drilling, which can lead to any number of difficulties in linking and igniting the gasifier. One test in the USA had an error in alignment for the directionally drilled CRIP, which resulted in the linkage distance to the product hole being too great. A less serious version of this problem occurred at Alcorisa, Spain where part of the CRIP dipped below the floor of the coal seam, so was in rock rather than coal. In both these cases this was a result of errors in site planning and surveying, in the USA due to the incorrect use of magnetic versus true north and in Spain the slope of the coal seam had been incorrectly calculated by 2-3°. These errors are obviously avoidable given experience operators and careful site planning.

Another type of drilling problem relates to the material through which the drilling is occurring. Obviously, very hard rock will add to the cost of drilling due to increased wear on equipment, however a large component of the drilling cost is in the usage of drilling mud. Drilling through overly porous material, such as old mine workings or possibly even disturbed soil, will lead to increased mud usage and may require more expensive techniques. In the extreme, it may be necessary to cement the material so that it can be drilled, which would add substantially to the cost and time taken. Similar problems can occur with soft coal seams, where the drilled hole can collapse on the drill. This can lead to loss of the drilling equipment.

(b) Poor flow from injection to product holes

This is a very common problem in early tests in the USA and probably also in the USSR, it also caused abandonment of the first Thulin test. Simplistically, it is caused by having low permeability material between the injection and production holes. A number of techniques have been tested in the USSR to increase this permeability. These include hydro-fracturing or explosive fracturing of the coal and passing electrical current between the holes, however the most reliable method, that has been almost universally adopted, is reverse combustion linking. This entails igniting the coal at one hole and supplying oxygen (or air) at the other, so that a path is burnt through the coal. Obviously, if no flow can be maintained this will not be successful and the holes will have to drilled closer together. The required spacing of the holes is therefore related to coal permeability. A discontinuity in the coal seam, which is suspected in the first Thulin test, will also cause flow problems and may mean that the site cannot be used for UCG.

(c) Inability to ignite the coal seam

Ignition of the coal seam has been achieved quite readily in most underground gasification trials, typically through the addition of a highly flammable substance and electrical ignition. However, in other trials it has proved extremely difficult, although it has been rare for ignition problems to result in abandonment of a test. Ignition is usually achieved through the addition of large quantities of liquid hydrocarbon fuels (eg. diesel) or occasionally through methane injection prior to subsequent ignition attempts. As a first step, silane is commonly used in shallow to moderate depth seams as it spontaneously combusts on contact with air, however this process is inhibited at high pressures and can therefore cause an ignition failures (eg. Huntly before another spontaneously combusting fluid was used). A common cause of ignition failures is high water ingress rates, which is particularly problematical with deep coal seams such as used during the Thulin trials. It appears that ignition is relatively simple where the coal seam contains significant quantities of methane.
(d) **Casing failure**
The piping used for the feed and product holes of the gasification site is subjected to various stresses, mainly caused by ground movement and high temperatures. In early Soviet tests the pipe failure rate was in excess of 20% of the pipes used, however this was reduced to less than 10% with experience and the use of improved grouting cements. The rate of failure was probably exasperated by reuse of the pipework in the Soviet operations and the shallow operating depths leading to heavy subsidence. Operational changes used to reduce the failure rate include angling the pipes to avoid the subsidence zone over the gasifier void and always maintaining some airflow into the gasifier to cool the pipes. Another cause of casing failure that is avoidable is high pressure, which is the result of inadequate pressure relief when a pipe becomes blocked. This affected the El Tremedal/Alcorisa test.

(e) **Roof collapse**
Roof collapse is a common occurrence in underground gasification operations and is a result of the growth of the gasifier void and thermal cracking of the overburden. Collapse can only be avoided by the retention of support pillars adjacent to the gasifier void, however it is more likely to be an accepted part of the site design with pillars being retained only to prevent excessive subsidence at ground level. In some cases roof collapse has caused serious problems in the gasifier, usually when it has resulted in blockage of the injection pipe. In the El Tremedal/Alcorisa test the roof collapse led to injection pipe damage and also a rapid increase in the water ingress rate due to the overburden being essentially wet sand. In order to minimise the impact of roof collapse on UCG activities a site design that accounts for the breakage characteristics of the overlying strata when exposed to thermal stress should be used. This will determine the maximum span that should occur between pillars and, possible, an acceptable rate of growth for the gasifier. A problem that can occur with excessive roof collapse is gas bypassing, caused when the injected gas passes through a void in rock, rather than coal, and therefore reaches the product hole without reacting. This has happened in a number of trials and can lead to a section of coal not being gasified. It is important to direct injected gases low in the coal seam to minimise the risk of this occurring.

(f) **Flooding**
The flooding of a gasification site will typically be related to some other operational problem. Coal seams are typically within aquifers, excepting if they are exceptional shallow seams, and therefore the gasifier void will resemble a bubble in the wet solid. The operating pressure of the gasifier will be sufficient to prevent excessive ingress of water but should not be overly high so as to reduce gas losses. In typical operation it is expected that water will flow into the lower part of the void but be held out at the higher parts, due to slightly higher hydrostatic pressure at the greater depth. If the operating pressure drops due to faults in the plant or a higher permeability section of rock is exposed with collapse of roofing material, water will flow in more rapidly and may extinguish the burning coal. Once the coal is extinguished it may prove difficult to re-ignite, as the water must be forced from the void and an ignitable section of coal exposed to a flame at sufficiently high temperatures. Flooding is therefore avoided by careful monitoring of the gasifier to control water ingress and possibly relocation of the injection point.

**Environmental risks of UCG**
Underground coal gasification avoids several of the environmental issues that affect the coal mining and utilisation industries, for example generation of spoil, the issue of handling water removed from mine workings, ash is left in the seam and the gas product produced is easily cleaned to produce a low pollutant product (especially relevant for high sulfur coals). However, the technique has its own issues that have to be addressed.

**Groundwater contamination**

*Past experience*
Groundwater contamination has been the major concern about the application of UCG, in particular in the USA. In large part this relates to the Hoe Creek III test in 1979, which led to the contamination of groundwater with phenols and other hazardous compounds (some contamination also occurred during the Hoe Creek II series of tests). Several studies on the cause of contamination have been conducted for this site and extensive remediation has been undertaken, not wholly successfully. Initially, it was thought that
the contamination occurred due to excessive pressures used during some stages of the tests. It was believed that this led to organic liquids being forced out of heat-affected coal and into the surrounding aquifer system. Remediation was undertaken by pumping water from the site through charcoal filters before reinjecting it into the aquifer. In the first attempt at remediation treatment, two million litres of water were treated in this way over a three-month period. This caused a rapid decline in phenol concentration, however levels remained well above the maximum allowed by the local environmental authorities (600-900 ppb compared to the maximum allowable limit of 20 ppb imposed by the state environmental authorities). In subsequent attempts, approximately 75 million litres of water have been treated via charcoal filtration, at both the Hoe Creek II and III sites, and also air-sparging and bioremediation trials have been performed. These later trials reduced levels of harmful organics to approximately the allowable maximum.

Since the discovery of these problems in the Hoe Creek area, further testing has been performed at other UCG sites in the USA. Tests at the Rawlins site were conducted to support an application for a licence to construct a commercial UCG plant at the site and did not identify any groundwater contamination, however the plant did not proceed for other reasons (increased availability of natural gas). Another UCG test was performed at the site in 1995 (Carbon County test) in order to satisfy environmental concerns during an application for a commercial operation licence. Some contamination of aquifers appears to have occurred, with some water tests around the site indicated extremely high levels of benzene (greater than 20 mg/l with the EPA limit being 5 mg/l for drinking water). The commercial plans were abandoned and remediation work required at the site. The Rocky Mountain test (at the site of the earlier Hanna series of tests) in the late 1980s was subject to greater environmental testing before, during and immediately after the trial. Contamination of aquifers was limited to the aquifer containing the subject coal and this was resolved through treatment of a minimal quantity of water from the aquifer during the shutdown procedures.

One of the issues in identifying contamination from the tests in the USA is that no testing was done before most of the trials, so it is difficult to identify where contamination is naturally occurring or due to the gasification activities. Most of the major trials were performed in Wyoming on federal government land, which was assumed to be exempt from state environmental laws. The issue of groundwater contamination was therefore neglected in the planning and operation of the gasification tests.

There is little literature on potential groundwater contamination for other test sites. At the depth that the recent European tests were performed it is unlikely that the surrounding groundwater would be used for any purpose, so little emphasis was placed on possible contamination. Olness reports limited groundwater data for the Lisichansk site, showing that there was a substantial increase in dissolved solids in the aquifer containing the coal seam that was gasified but surrounding aquifers were minimally affected. No data were presented for organics in the water. The concentrations of dissolved salts in the aquifer decreased to similar levels as the surrounding waters over a 2 to 5 year period after testing was completed. Notably the Lisichansk site had substantially lower subsidence than most other Soviet test sites, so more disturbance of aquifers would be expected at other sites for which no groundwater contamination data are available. Another Soviet site with some reported groundwater analyses is Yuzhno-Abinsk. Minimal organic contamination of aquifers occurred, only marginally above the US EPA specified limit for drinking water, and was only evident about the period of gasification activities in the vicinity of the gasification void. Levels decreased to near the background readings within several months of gasification activity ceasing in the area tested.

A curious issue in the contamination of aquifers due to disturbance caused by collapse of overlying strata into the gasification void is that this type of collapse would also occur during some conventional mining operations. Covell and Thomas (1996) determined that groundwater would be contaminated to levels above the permissible limits simply by coming into contact with unaltered coal at Hoe Creek. Long-wall mining causes a similar type of collapse and it could be expected that in some locations an overlying aquifer would be diverted to flow through disrupted sections of the mined coal seam. As long-wall mining is far more common than underground gasification and it appears that the source of contaminants
can be coal, rather than heat affected coal, it would be expected that similar contamination had occurred during conventional mining operations.

**Avoidance techniques**
A series of best management practices has been defined by the US EPA\textsuperscript{26} for in-situ fossil fuel processes. These are:

- Wells should be constructed so that they are not subject to subsidence or rock deformation damage and the casing materials are unlikely to fail at the temperatures and pressures likely to occur during operation.
- The operating pressure used should be set to minimise gas losses from the void and prevent migration of contaminants into surrounding aquifers. The gas flow rate through the void should be maintained so that ground water and contaminants are carried with the product gas to the surface, that is the velocity should be above droplet entrainment velocity at the product hole.
- Monitoring of the burn front should be performed at all times to ensure that the integrity of the injection and production piping is not affected.
- Flushing of the void and complete plugging of the underground piping should be carried out on closure of the site. In some cases, complete filling of the void may be warranted. Flushing can be carried out with water or steam and more recent trials in the USA have performed this several times to remove any liquid pyrolysis products from the voids.

Complementary to these practices are methods developed by researchers in the former Soviet states. These include:

- Use of a drainage well during gasification to remove surplus water and contaminants from the void. This was developed as a means of preventing quenching of the gasification process by excess water inflow, however it provides a means of operating at lower gasification pressure which will reduce the likelihood of contaminants being forced into the surrounding aquifer\textsuperscript{22}.
- Retaining protection pillars around the gasification void to prevent catastrophic roof collapse. Protection pillars are used to prevent the interconnection of operating and abandoned sections of a gasification field and to prevent excessive subsidence that could lead to gas leakage and disruption of the aquifer system. Calculation of the size of pillars required is possible where an understanding of the site geology is comprehensive\textsuperscript{23}.

**Subsidence**

**Past experience**
Little has been published on the extent of subsidence at ground level during the gasification trials in the USA. At the time of the tests the subsidence may not have been evident, however later observations suggest that subsidence occurred as pot holing at some of the sites. The groundwater contamination issues discussed above certainly suggest that subsidence should have been noticeable, considering the extreme disruption of aquifers at some sites. Therefore, it is likely that little care was taken to observe environmental impact in the early USA trials. In early Soviet work, subsidence was extreme due to the shallow seams being utilised. It was common practice to deposit truckloads of clay into cracks in the ground. Sometimes these cracks exposed the gasification process occurring underground. In later Soviet work the subsidence appears to have been controlled, with the land returned to agricultural use shortly after the gasification site was exhausted. Overall, in a well-designed and tightly controlled gasification site it would be likely that subsidence would be similar to that expected after long-wall mining of the same coal seams at the same depth. It is unlikely that the thermal effects of gasification on the overlying rock strata would lead to considerably greater subsidence.

**Avoidance techniques**
The avoidance of excessive subsidence would rely on essentially the same approach taken in other coal extraction techniques. An acceptable subsidence level would depend on the land use and situation, and this would be used in the site design and establishing operating techniques. Obviously, massive subsidence at the operating face of the gasifier would be detrimental to the site operations, so subsidence would normally be limited by the retention of pillars\textsuperscript{23}. Some of these pillars would be used to control the
direction of gasification progress during the operations and then be removed after specific areas of coal had been removed, while others would be retained to support the roof or seal sections. Of course, the nature of the overlying strata would influence the requirements for supporting pillars. Low subsidence techniques can be applied for shallower seams. This involves gasifying only narrow strips of coal, so that the unsupported span of roof is not wide enough to collapse. With time it would be expected that some subsidence would occur, but it could be delayed by this approach to occur after UCG operations had ceased. This would have a similar behaviour to bord and pillar mining, so it is likely that in the long term subsidence would occur primarily at junctions between gasified tunnels.

**Contaminated water**

The volume of wastewater arising from underground coal gasification should be much less than from conventional mining, however the stream from the gas scrubbers will include a high concentration of organics, such as phenols, that will require proper disposal techniques. In the majority of tests performed the volumes of contaminated water have been such that trucking of the water away from the site to suitable disposal facilities has been sufficient. In the large Soviet operations, the product gas has been burnt in a power station boiler, so removal of the organics has not been necessary. The UCG gas at Angren is now scrubbed before piping to the power station. This avoids long-term issues, such as deposition in the pipes. There is some economic value to the organic components and it has been found that the cost of processing these into a saleable form is justifiable. It is also possible to extract the organics and dispose of them by injection into the hot region of the gasification void, however it would have to be shown that this would not increase the likelihood of contamination of underground waters. Alternatively, a high temperature flare could be used.

**Methods of control for UCG**

There are limited controls and monitoring devices that are suitable for UCG sites, providing an unusual challenge in monitoring and control of the process. Control is restricted to the operating pressure and flowrates of oxygen/air and steam/water, and possibly also an inert gas such as nitrogen. Monitoring using inserted devices, such as thermocouples, is expensive, so remote monitoring of the flame front will typically be performed using methods such as reflected high frequency waves\textsuperscript{27}, sound detection or emission of radioactive materials from the coal. These techniques are not particularly reliable however, so control is likely to rely on measurement of the product gas composition, temperature and pressure. This will lead to a feedback control loop with substantial lag, which may lead to excessively slow response when large changes occur in the void, such as roof collapse or piping failures.

The shortcomings in control have been countered in the Soviet work, and proposed commercial sites in the USA, by operating numerous gasifiers in parallel. This results in a stable product gas composition by combining the gas from the different gasifiers, preferably using gasifiers in varying states of development to allow a progressive introduction of new gasifiers as old gasifiers exhaust. A typical commercial application would, for example, supply a 250 MWe gas turbine using in excess of 20 single CRIP gasifiers that each have approximately a one-year operational life. Each gasifier would be monitored separately and have individual control over flow rates of oxygen and water or steam, however overriding control would occur to ensure that the total gas flow and composition meets the plant requirements.

A more advanced control option is the use of model-based control to simulate the behaviour of the gasification field in real-time. This would provide a predictive tool that can be used to optimise performance of the gasification site through provision of set-points for the feed flows and operating pressure for each gasifier. Development of these types of systems has progressed, but in the most recent European trials the modelling effort lagged substantially behind the progress of actual gasification.

The desired nature of the product gas is important in selecting feed rates, as methane formation is favoured at lower temperatures (~800-900°C) and higher pressures. However, the low reaction rates at low temperatures tend to limit the throughput of the gasifier, so higher temperatures are often sought (~1200-1300°C) with resulting higher concentrations of carbon dioxide and hydrogen. Higher temperatures also reduce the quantity of tar produced. From past operating experience it appears that
lower operating temperatures have been either favoured during the tests or have been the result of high water ingress rates. If a high concentration of carbon monoxide and hydrogen in the product gas is required, for example in synthesis applications, it is possible to treat the gas through a catalytic shift reactor to convert unwanted methane. In gas turbine applications high methane content is preferable and this can be maximised through operating the gasifier under moist, high-pressure conditions.

In terms of product gas calorific value only, Soviet research performed at the Podmoskovia/Tula site suggested that the air flow rate should be maintained at 3000-3500 m$^3$/hr for a 3 m thick coal seam and 5000-6000 m$^3$/hr for a 6 m coal seam to obtain optimum calorific value in the product gas. It was extrapolated that an airflow rate of 15,000-20,000 m$^3$/hr would be optimal for coal seams of greater than 10 m thickness. Unfortunately, similar work has not been reported for oxygen gasifiers, however it would be expected that the results would be approximately one quarter of those established with air. Operational guidelines for the site include:

- Operational pressure of the gasifier should be approximately equal to the hydrostatic pressure at gasification depth to reduce both gas leakage water ingress rates
- Piping should be inserted so that subsidence or rock deformation on heating are unlikely to damage it as gasification proceeds
- The burn front should be monitored, through instrumentation and/or modelling, to ensure that it does not spread to outside the nominated gasification area
- Protective pillars of coal should be maintained to minimise subsidence and prevent interaction of the current void with other operating or decommissioned gasifier voids
- On completion of gasification activities in an area, the void should be flushed with steam and/or water to remove undesirable compounds that may subsequently contaminate groundwater.

**Clean Cavern Concept**

An operating methodology similar to the Soviet operating guidelines was developed in the USA in order to optimise the environmental performance of UCG while maintaining satisfactory operational performance. It eventuates that these two objectives are linked, as maximisation of resource recovery in the gas corresponds to minimisation of organic dispersion into the groundwater. The simple basis of the Clean Cavern Concept is that all materials should flow towards the cavity during operation, so gas and organics are either retained in the cavity or are withdrawn as product. This reduces the loss of product gas during operation and, therefore, improves the efficiency of operation. The only obvious negative is that the operating pressure cannot be increased above the hydrostatic pressure to increase reaction rates. The issue of how to deal with materials left in the cavity occurs when gasification of an area is completed. If the process has been well operated only minimal quantities of tar should be left present and the concept is to react these with steam while the cavity is still hot. Steam tends to cause decomposition of large organic molecules. The cavity is allowed to fill with water under a controlled depressurisation as it cools and the water is then pumped out to remove any dissolved organics. If required, a second refill and pump out can be used. This approach was used for the Rocky Mountain 1 and Chinchilla UCG operations and appears to have been successful in avoiding contamination of surrounding groundwater.
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APPENDIX B: ACID GAS REMOVAL AND SHIFT REACTORS

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Following is the description of the acid gas removal process and the associated capital and operating cost estimations as applicable to removal of CO₂ and H₂S from the raw synthesis gas from the underground coal gasification facility and a Destec surface coal gasification plant. These methods were used to provide a comparative estimation of utilities requirement and costs for the acid gas removal from synthesis gas as applicable to both above and below ground coal gasification. The Selexol process was selected for acid gas removal since very low sulfur coal has been used for gasification and elemental sulfur recovery was not required. Destec coal gasification technology was selected for comparison with the underground coal gasification as the source of synthesis gas for power generation. The effect of water gas shift on the raw synthesis gas and removal of CO₂ from the shifted gas using the Selexol process has also been investigated for both the above and below ground gasification units. Both hot and cold shifts were employed to increase hydrogen concentration of the synthesis gas. CO₂ removal to 90% by volume and complete removal of H₂S from shifted and non-shifted synthesis gas was aimed for both above and below ground coal gasification processes.

Selexol Process:

The Selexol process is an absorberStripper system that uses dimethyl ether of polyethylene glycol as a physical solvent for removal of H₂S and CO₂ from synthesis gas. It has been adopted as a standard process on many commercially operating petroleum coke and coal based integrated gasification combined cycle power plants for removal of sulphur species and CO₂ prior to firing gas turbines. It is well suited where the process gas is available at least at 2 MPa. For the present analysis, the Selexol absorber tower was considered to operate at 30 °C and 8 MPa and accordingly the raw synthesis gas was compressed from 2.3 MPa to 8 MPa using an inter-cooled 4 stage gas compressor with a gas expander on the same shaft. Fig 1 shows the process flow diagram for the Selexol process. Where the water gas shift was carried out upstream, the synthesis gas was cooled from the low temperature shift reactor temperature to 47 °C prior to compression to the Selexol absorber operating pressure by exchanging the heat with the cold CO₂ lean gas leaving the Selexol absorber. The raw compressed gas at 47 °C was cooled in a chiller to 30 °C prior to entering the absorption tower. The acid gas loaded solvent collected at the bottom of the tower was passed through hydraulic turbines and several pressure let down sequences to regenerate the solvent. To improve the H₂S removal efficiency, CO₂ rich off-gas from the high-pressure flash drum (2 MPa) was recycled to the absorber inlet. CO₂ lean synthesis gas leaving the absorption tower at the top was expanded to 2.3 MPa to balance the inlet compression power load. The regenerated lean Selexol solvent was recycled to the absorber and the product acid gases (mainly CO₂) were collected separately at 100 kPa (g) and 20 °C. Further details for the Selexol acid gas removal process have been given elsewhere.¹ The material and energy balances for the acid gas removal were calculated using the Excel Spreadsheet based simulation model developed in-house, which relies on the public domain CO₂ and H₂S gas solubility data at 30 °C and 80 bar in the Selexol solvent. Table 1 below gives the utility requirements and the capital and operating costs associated with the acid gas removal.

The capital and operating costs are in Australian dollars and sourced from the US DOE reports² assuming one to one parity between the Australian and US currencies. This approach is valid since all of the equipment associated with the Selexol acid gas removal system and the water gas shift reactors can be obtained locally. The US currency dominated costs are perhaps applicable only to the proprietary Selexol solvent (dimethyl ether of polyethylene glycol) and the water gas shift catalysts, which are standard off the shelf items. Accordingly, these items were costed at AUS $1 = US $0.71. The following assumptions were also made while arriving at the capital and operating costs shown in Table 1.

- Engineering fee is 10% of the bare equipment cost.
- Project contingency is 10% of the bare equipment cost.
- Prepaid royalties are 0.5% of the bare equipment cost.
- The cost of spare parts is 0.5% of the bare equipment cost.
The annual plant maintenance cost is 2% of the bare equipment cost.

References used in this Appendix

Table B.1: Selexol Acid Gas Removal Utility Requirements and Costs

<table>
<thead>
<tr>
<th>Case</th>
<th>Destec Fuel Gas</th>
<th>Destec Shifted Fuel Gas</th>
<th>UCG Fuel Gas (Good)</th>
<th>UCG Shifted Fuel Gas (Good)</th>
<th>UCG Fuel Gas (Bad)</th>
<th>UCG Shifted Fuel Gas (Bad)</th>
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<tbody>
<tr>
<td>%CO2 Removal</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
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<td>90</td>
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<td>Plant Capacity Factor (%)</td>
<td>85</td>
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<td>85</td>
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<td>Inlet Gas Pressure, (MPa)</td>
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<td>2.76</td>
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<td>Inlet Temperature, (°C)</td>
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<td>45</td>
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<td>Dry Basis Inlet Flow Rate, (m3/hr)</td>
<td>11276</td>
<td>18884</td>
<td>8817</td>
<td>15352</td>
<td>9954</td>
<td>17043</td>
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<td>Dry Basis Inlet CO2 Vol, %</td>
<td>8.5</td>
<td>38.3</td>
<td>28.8</td>
<td>42.8</td>
<td>32.2</td>
<td>43.9</td>
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<td>CO2 Lean Gas Flow Rate, (kmols/s)</td>
<td>2.57</td>
<td>3.04</td>
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<td>2.07</td>
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<td>CO2 Rich Gas Flow Rate, (tons/hr)</td>
<td>34.0</td>
<td>254.0</td>
<td>98.0</td>
<td>232.0</td>
<td>133.0</td>
<td>263.0</td>
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<td>Selexol Makeup Rate, (kg/s)</td>
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<td>0.004</td>
<td>0.001</td>
<td>0.003</td>
<td>0.001</td>
<td>0.003</td>
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<td>Power Consumption (MW)</td>
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<td>32.4</td>
<td>8.7</td>
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<td>Chilled Water Refrigeration Load, (MW)</td>
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<td>3.1</td>
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<td>Cooling Tower Heat Load, (MW)</td>
<td>6.9</td>
<td>31.1</td>
<td>3.5</td>
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<td>25.3</td>
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<td>Capital Cost (exclusive of land cost), $</td>
<td>78,940,000</td>
<td>69,165,000</td>
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<td>61,150,000</td>
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<td>Selexol Make-up Cost (@ $3.5/kg), $/year</td>
<td>94,000</td>
<td>376,000</td>
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<td>282,000</td>
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<td>Shift Catalyst Cost, ($/year)</td>
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<td>Plant Annual Maintenance Cost, ($/year)</td>
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<td>490,000</td>
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