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## Technology Primer on Underground Coal Gasification

Dr Andrew Beath  
ET/IR990  
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Prepared for Carbon Energy Pty Ltd  
PO Box 887, Kenmore QLD 4069

Enquiries should be addressed to:

Dr Andrew Beath

CSIRO Energy Technology

10 Murray Dwyer Cct

Mayfield West NSW 2304

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## Executive 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 and a small-scale operation has been operating in South Africa with plans to expand to supply fuel for a coal-fired power plant. 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 200 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, so that gas blending can be used to produce a uniform product. 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 for commercial operations, 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 under the current legislation, but is expected to provide a cheaper route to low Greenhouse emission electricity than other proposed clean coal technologies. Electricity cost and emission legislation is specific to individual countries, so viability may vary 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 but are subject to uncertainty regarding the sensitivity of the utilisation process to the UCG product gas. Further examination of the economics of processes to convert the gas into various liquids would be required to verify this.

In addition to a broad ranging report on the technology of underground coal gasification this document also includes a summary of an example analysis of the likely performance of a process incorporating underground coal gasification for electricity generation at a specific site and a one-day tutorial in presentation form that has been prepared. This covers essentially the same material as the report in a series of presentations on the following underground coal gasification topics:

- Fundamentals
- Plant design
- Behaviour prediction
- Process performance & economic viability
- Groundwater & surface impacts
- Site selection & characterisation
- Social perceptions
- Case study analysis

Additional presentation material is also included on historical UCG activities, modelling of UCG, simulation of power processes and modelling of ground deformation. This report was prepared by CSIRO for Carbon Energy Pty Ltd using material sourced from CSIRO, Carbon Energy and Mr Burl Davis.

# 1. Technology overview

## Introduction

Underground coal gasification (UCG) is a technology that can be used to extract coal resources that are either not accessible by conventional mining technologies or are not economic to extract conventionally. Primarily, this refers to coal seams that are too deep to open-cut mine and contain poor quality coal that is not attractive for conventional underground mining methods. It is expected that the successful application of underground coal gasification could increase massively the size of economically extractable coal resource in Australia and could also promote the establishment of new coal-based industries that utilise the generated gas to produce a range of chemicals or electricity. This technology overview covers a range of topics that are important to the selection and operation of underground coal gasification sites, as well as general information on the technology and its history. A tutorial presentation covering much of the same material is also included in Section 3 and some additional presentation material on specific topics is given in Section 4.

The concept of UCG has been around for over 100 years and there have been operations in countries of the former Soviet Union since the 1930s, with some plants being currently operating with over 40 years of operational experience. In the western world there have been sporadic experimental programmes since the 1950s, with extensive experimentation in the 1970s and 1980s in the USA and experimental programmes in western Europe in the 1980s and 1990s, carrying through to a current research programme in the United Kingdom. China and India also have active programmes intending full commercial implementation and a demonstration of a version of the technology was performed in relatively shallow coal (130m) by Linc Energy from 1999 to 2001 at Chinchilla, Queensland. Eskom in South Africa has also announced that it has a small plant operating that is currently providing 80% of the fuel for a diesel engine, but will be expanded to provide fuel gas partially replacing coal as feed to produce 700MWe from a coal-fired power station.

The basic operating principles of a UCG site are relatively simple, injection and production wells are constructed from the surface to the coal seam and coal is gasified by partial combustion using either air or oxygen injected from the surface. The product gas is extracted and, after cleaning, can be used as a fuel (eg. in a power station boiler or a gas turbine) or for the synthesis of chemicals (eg. liquid fuels, such as diesel or petrol, or ammonia for fertiliser production). There are significant variations of the technology that are suited to different types of resource, some using arrangements of vertical or slanted wells and others using directionally drilled surface to in-seam wells.

The past experiences with UCG technologies worldwide have been fairly well documented, with most of the research being funded by governments and the results being openly published. For this reason, the systemic problems with the various forms of the technology have been disclosed and made the subject of discussion and further research over several decades. There are two key issues that remain to be addressed, namely the environmental risks and the robustness of monitoring and control systems. The environmental risks remain an issue because there has been an increase in sensitivity in this area with time, so the earlier experimental trials are unlikely to have been performed with a currently acceptable environmental performance. It is therefore necessary to ensure that future UCG developments can be performed to a satisfactory environmental standard. Monitoring and control are areas that it is expected that improvements in technology, for example more accurate drilling and remote sensing, are likely to result in increased potential for the technology. In the past most UCG product gas it has been difficult to maintain consistent product gas quality during long term UCG operations. This is not a major concern when the gas is being used as supplementary fuel for a coal-fired boiler, such as in the Soviet applications, but is of concern when it is used as feed for gas turbines or synthesis plant. Therefore, if UCG technology is to be applied for

modern applications, it is necessary to improve control over the process and this is likely to occur only through an improved understanding of the behaviour of the site during operations, firstly through modelling before operations commence and then monitoring during operations.

## **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, 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 high to moderate 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 in 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.

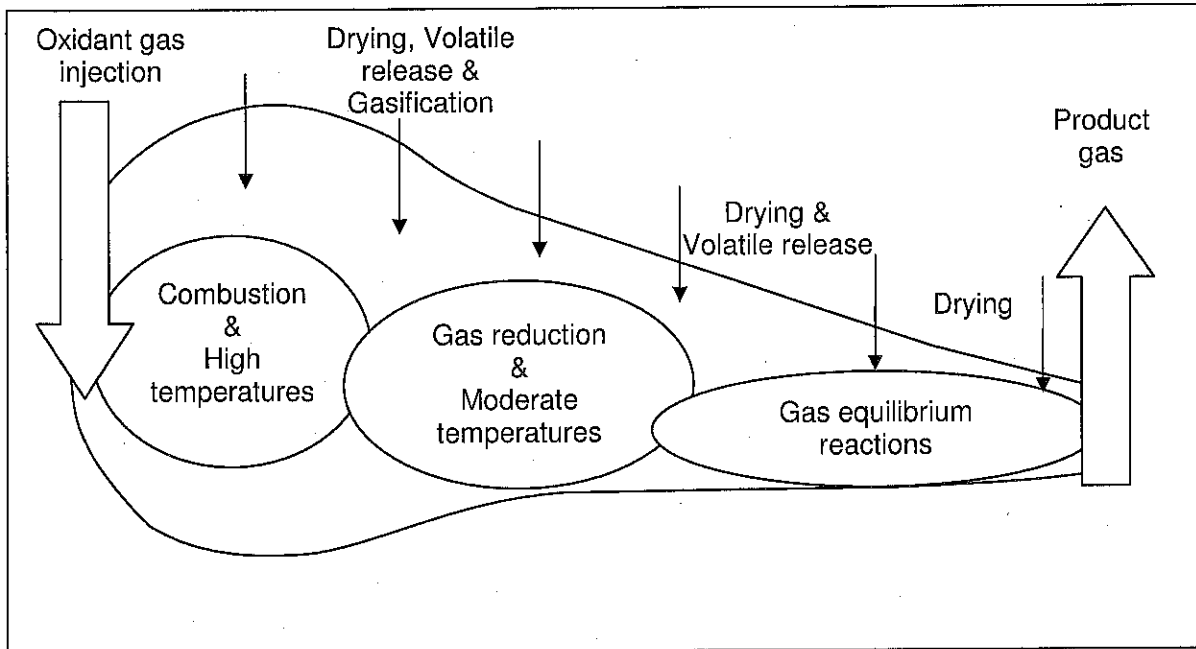


Figure 1: Schematic of the processes involved in UCG

## Historical experience

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 2 and brief information on the most sites is given in Table 1.

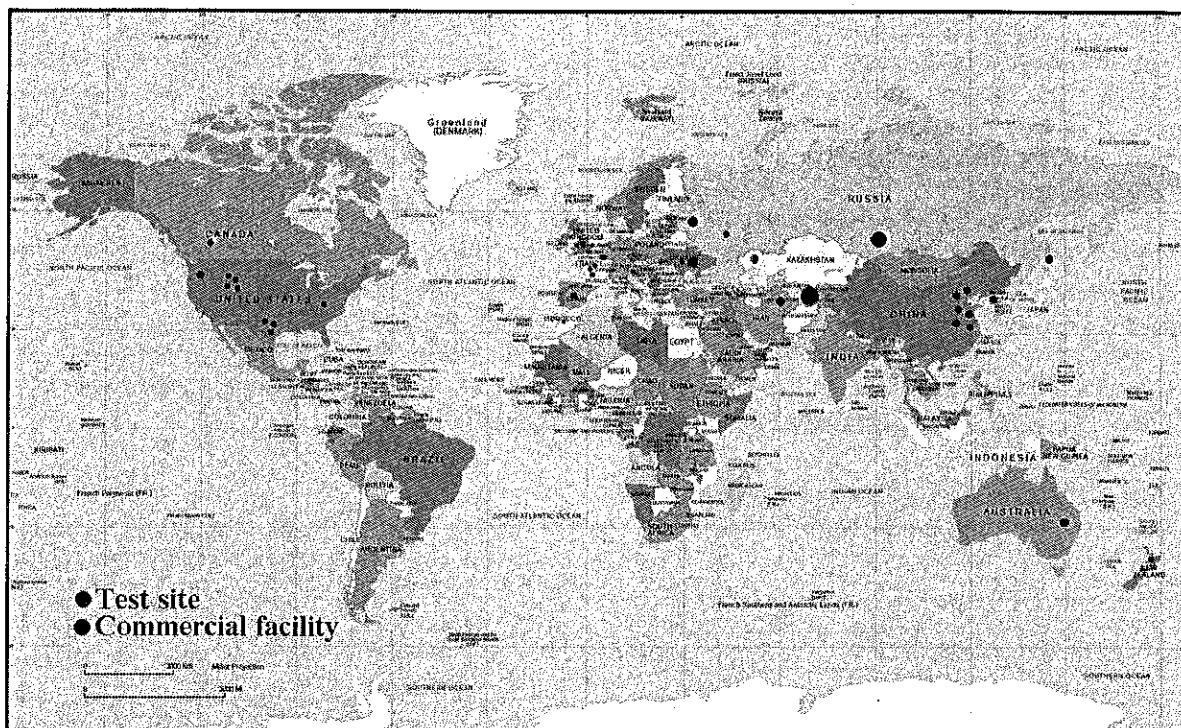


Figure 2: Map indicating approximate locations of UCG trials

Of all the UCG sites used, there has only been constructive use of the product gas at several Soviet sites, several sites in China and reportedly one site in 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 sites have been used to generate a product gas with a high concentration of hydrogen that is purified using pressure swing adsorption, town gas for domestic fuel and synthesis gas for ammonia production, but all on a relatively small scale. In addition, a recent announcement by the South African electricity generator Eskom claimed operation of a small diesel engine with 80% of the fuel from UCG, with plans to expand the UCG operation to provide 700MWe of electricity through co-firing in coal-fired boilers.

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<sup>28</sup>. 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 ( $\sim 5.0 \text{ MJ/m}^3$ ), 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 1: Summary of past UCG experiments

Test	Year	Coal type	Technique	Seam thickness m	Seam depth m	Feed gas	Product gas CV MJ/m <sup>3</sup>
Krutova (USSR)	1933-1935	Brown	Chamber	2.5	15	Air	4.14
Shakhty (USSR - Russia)	1933-1934	Anthracite	Chamber	0.38	n/a	Air	3.87
Krutova (USSR)	1933-1935	Brown	Chamber	1.75	20	Air	4.14
Leninsk-Kuznets (USSR - Kazakhstan)	1934-1936	Bituminous	Stream	4.85	28	Air	10.04
Lisichansk (USSR - Ukraine)	1934-1963	MVBit, low ash	Chamber	0.4	400	Oxygen	3.21
Lisichansk (USSR - Ukraine)	1934	Bituminous	Chamber	0.75	24	Air	3.78
Lisichansk (USSR - Ukraine)	1934	Bituminous	SingleV	0.75	24	Air	3.77
Lisichansk (USSR - Ukraine)	1934	Bituminous	SingleV	0.75	24	Oxygen	10.46
Gorlovka (USSR - Ukraine)	1935-1941	n/a	SDB	1.9	40	Oxygen	5.83
Gorlovka (USSR - Ukraine)	1937-1939	n/a	SDB	1.9	40	Air	3.97
Gorlovka (USSR - Ukraine)	1937-1939	n/a	SDB	1.9	40	Air	3.92
Gorlovka (USSR - Ukraine)	1937-1939	n/a	SDB	1.9	40	Oxygen	5.82
Gorlovka (USSR - Ukraine)	1937-1939	n/a	SDB	1.9	40	Oxygen	8.50
Gorlovka (USSR - Ukraine)	1937-1939	n/a	SDB	1.9	40	Oxygen	10.34
Podmoskovia/Tula (USSR - Russia)	1940-1962	High ash brown	VW	2	40	Oxygen	5.92
Podmoskovia/Tula (USSR - Russia)	1940-1962	High ash brown	VW	2	40	Oxygen	5.92
Lisichansk (USSR - Ukraine)	1940-1941	Bituminous	Stream	2.7	138	Air	2.57
Gorgas (USA)	1946-1952	HVB	VW	1	55	Air	5.18
Gorgas (USA)	1946-1952	HVB	VW	1	55	Air	4.39
Gorgas (USA)	1946-1952	HVB	VW	1	55	Oxygen	9.07
Bois-la-Dame (Belgium)	1948	Anthracite	VW	1	n/a	Air	n/a
Mars (Poland)	1950	n/a	VW	1	30	Air	3.50
Mars (Poland)	1950	n/a	VW	1	30	Oxygen	8.60
Djerada (Morocco)	1950-1955	Anthracite	VW	1	n/a	Air	n/a
Newman Spinney (UK)	1950-1959	Subbit	Tunnel	1	75	Air	n/a
Yuzhno-abinsk (USSR - Siberia)	1955-1989	LVBit, low ash	SDB	2	n/a	Air	12.11
Yuzhno-abinsk (USSR - Siberia)	1955-1989	LVBit, low ash	SDB	2	n/a	Air	8.81
Angren (USSR - Uzbekistan)	1962-1989	Brown low ash	VW	4	110	Air	3.88
Angren (USSR - Uzbekistan)	1962-1989	Brown low ash	VW	4	110	Air	3.49
Shatsky (USSR - Ukraine)	1965-1974	High ash brown	VW	0.3	11	Air	n/a
Hanna I (USA)	1973-1974	HVC-NS	VW	9.1	120	Air	4.49
Hanna IIA (USA)	1975-1976	HVC	VW	9.1	84	Air	5.02
Hanna IIB (USA)	1975-1976	HVC	VW	9.1	84	Air	5.22
Hanna IIC (USA)	1975-1976	HVC	VW	9.1	84	Air	6.20



Test	Year	Coal type	Technique	Seam thickness m	Seam depth m	Feed gas	Product gas CV MJ/m <sup>3</sup>
Hanna IID (USA)	1975-1976	HVC	VW	9.1	84	Air	5.02
Hoe Ck I (USA)	1976	HVC	VW	7.5	40	Air	3.67
Fairfield (USA)	1976	n/a	n/a	n/a	n/a	Air	4.70
HannaIII (USA)	1977	HVC	VW	9.1	84	Air	4.00
Hoe Ck IIA (USA)	1977	HVC	VW	7.5	40	Oxygen	9.51
Hoe Ck IIB (USA)	1977	HVC	VW	7.5	40	Air	3.88
Hanna IVA (USA)	1977-1979	HVC	VW	9.1	84	Air	3.71
Hanna IVB (USA)	1977-1979	HVC	VW	9.1	84	Air	4.90
College Station (USA)	1977	n/a	n/a	n/a	n/a	Air	4.20
Tennessee ColonyA (USA)	1978-1979	n/a	n/a	n/a	n/a	Air	3.00
Tennessee ColonyB (USA)	1978-1979	n/a	n/a	n/a	n/a	Air	8.60
Rocky Hill/Reno Junction (USA)	1978	Subbit	VW	30	190	Air	7.47
Hoe Ck IIIA (USA)	1979	HVC	VW	7.5	40	Air	4.12
Hoe Ck IIIB (USA)	1979	HVC	VW	7.5	40	Oxygen	7.18
Pricetown (USA)	1979	Bit-S	VW	1.8	270	Air	6.12
Rawlins-1A (USA)	1979	SubbitB	SDB	18	30	Oxygen	8.00
Rawlins-1B (USA)	1979	SubbitB	SDB	18	30	Air	5.80
Bastrop County (USA)	1979-1980	n/a	n/a	n/a	n/a	Air	5.60
Rawlins-2 (USA)	1981	SubbitB	SDB	18	130	Oxygen	11.92
Bruay-en-Artois (France)	1981	Anthracite	VW	1.2	1200	Air	n/a
Thulin (Belgium)	1982-1984	SA-NS	VW	6	860	Air	n/a
Centralia/TonoA (USA)	1984-1985	SubbitC	CRIP	11	61	Air	8.94
Centralia/TonoB (USA)	1984-1985	SubbitC	CRIP	11	61	Air	10.65
Rocky Mtn-1A (USA)	1985-1988	Subbit	CRIP	7	110	Oxygen	8.96
Rocky Mtn-1B (USA)	1985-1988	Subbit	VW	7	110	Oxygen	8.17
Haute-Deule (France)	1985-1986	Anthracite	VW	2	880	Air	n/a
Thulin (Belgium)	1986-1987	SA-NS	CRIP	6	860	Air	3.33
Thulin (Belgium)	1986-1987	SA-NS	CRIP	6	860	Air	9.03
Thulin (Belgium)	1986-1987	SA-NS	CRIP	6	860	Air	11.15
Huntly 5-spot (NZ)	1994	n/a	VW	10	320	Air	n/a
Liuzhang (China)	1997	MVBit	Tunnel	2	n/a	Steam	12.80
El Tremedal/Alcorisa (Spain)	1997	SubbitC	CRIP	2	600	Air	9.56
Xinhe (China)	1997	n/a	Tunnel	n/a	n/a	Steam	14.60
Anju (Nth Korea)	1999-?	n/a	n/a	n/a	n/a	Air	n/a
Chinchilla (Australia)	1999-2001	Bituminous	VW	10	130	Air	6.59
Liuzhang (China)	2001	MVBit	Tunnel	2	n/a	Steam	11.50
Suncun (China)	2001	Bituminous	Tunnel	2	80	Air	10.80
Xinhe (China)	2001	n/a	Tunnel	n/a	n/a	Steam	12.20
Xiyang (China)	2002	Anthracite	Tunnel	4	200	Air	6.20
Xiyang (China)	2002	Anthracite	Tunnel	4	200	Air	4.00
Suncun (China)	2002	Bituminous	Tunnel	2	80	Air	8.50
Xiezhuang (China)	2002	Bituminous	Tunnel	2.6	n/a	Steam	12.20

**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.

Additional presentation material on the history of UCG is given in Section 4.

## 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.

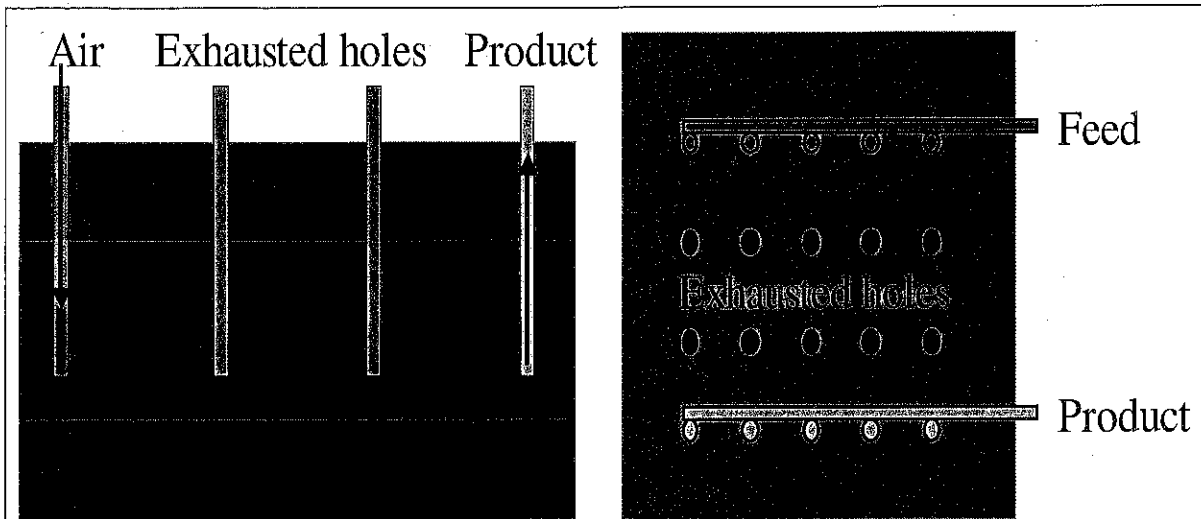
This simplifies control over the gasification procedure as all other techniques result in a changing reaction area with time. It is expected that the CRIP can be made self-retracting through selection of grades of steel such that the pipes that will melt when in contact with the burning coalface.

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.

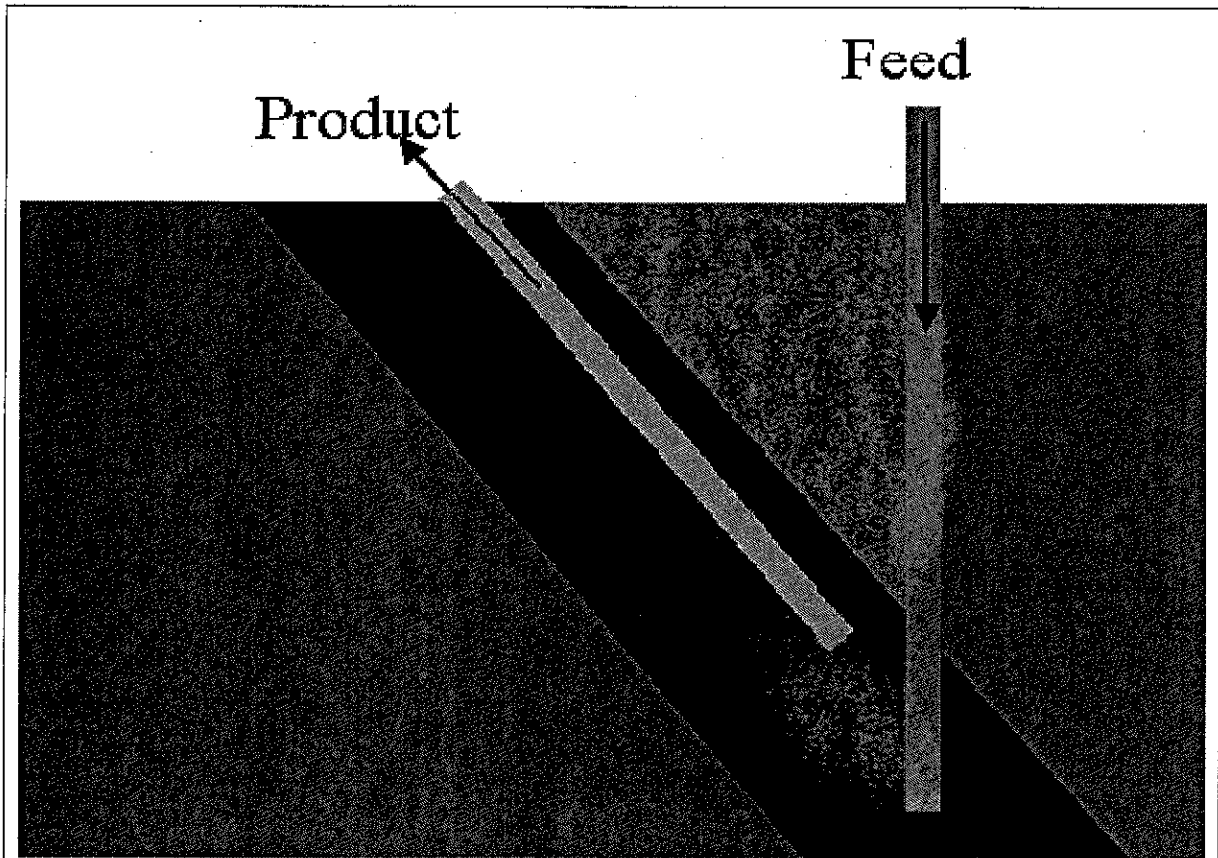
### Vertical wells:



### 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).

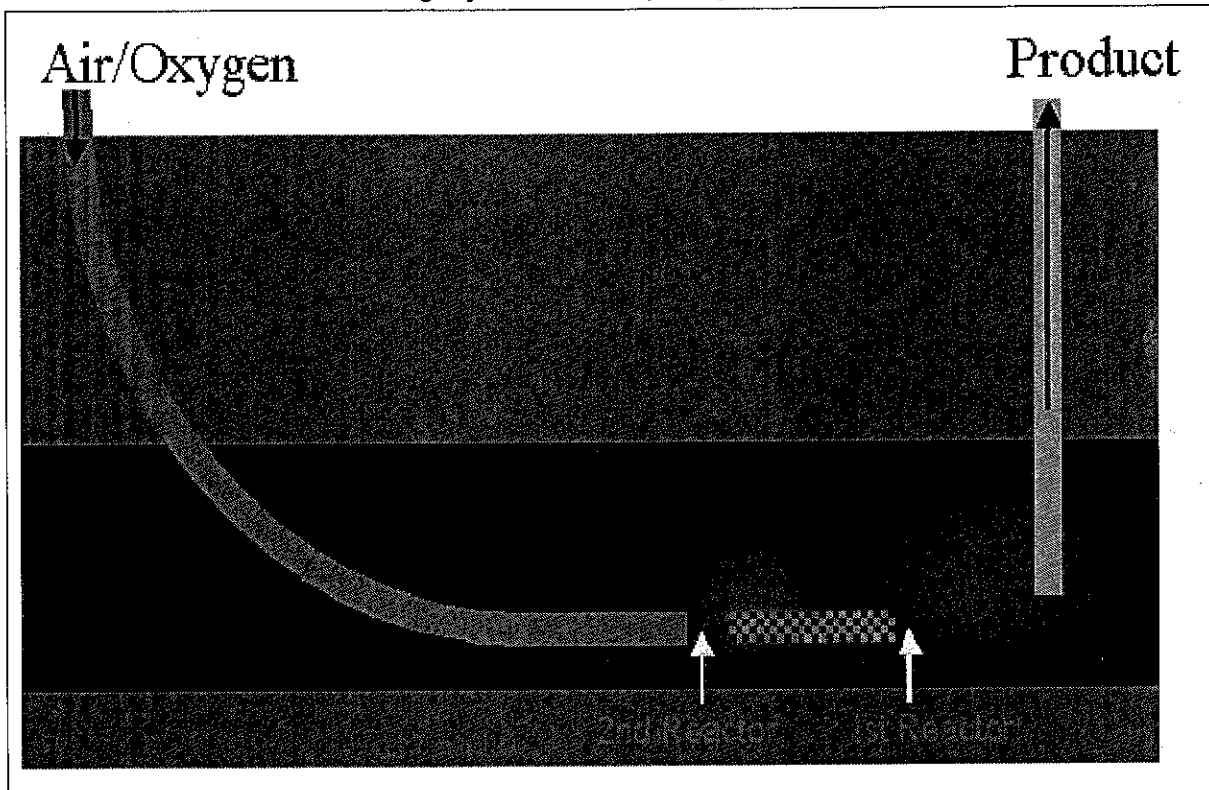
### Steeply Dipping Bed (SDB) technique



#### 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.

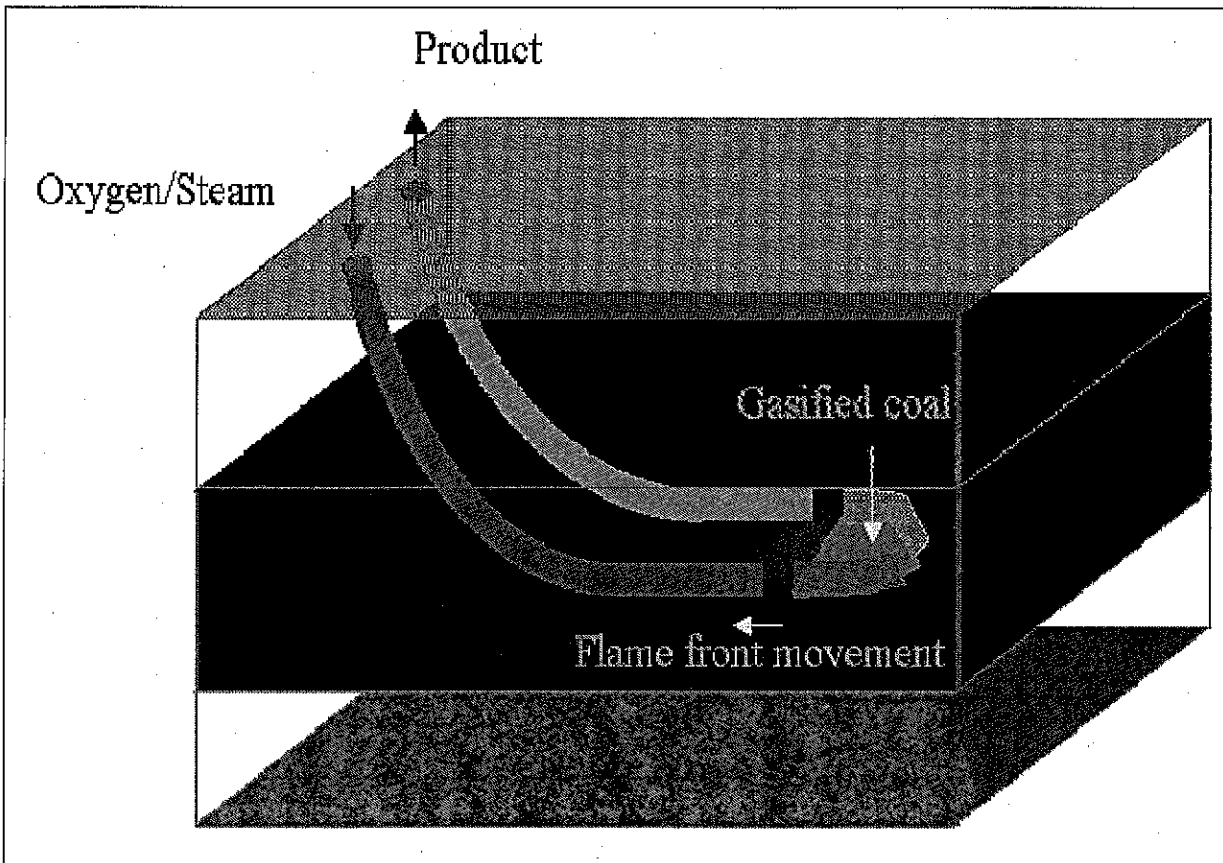
## Standard Controlled Retracting Injection Point (CRIP) technique



### 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.

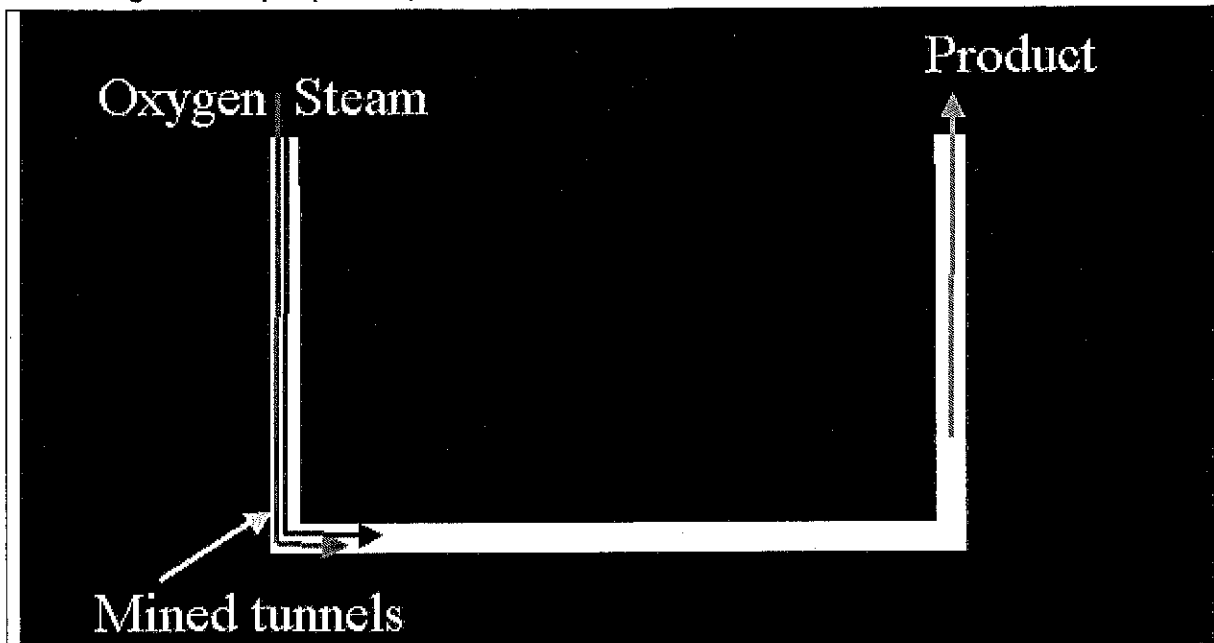
### Knife-edge CRIP



#### 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 technique 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.

### Two Stage technique (Tunnel)



#### 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 15 sites in China have used this technique, with various minor differences in design, and it has been in commercial use, but on a very small-scale. Most sites are now closed.
- 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 5years 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 3 and as the calorific value of the product gas as a function of coal seam depth in Figure 4 and coal seam thickness in Figure 5, 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 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%.

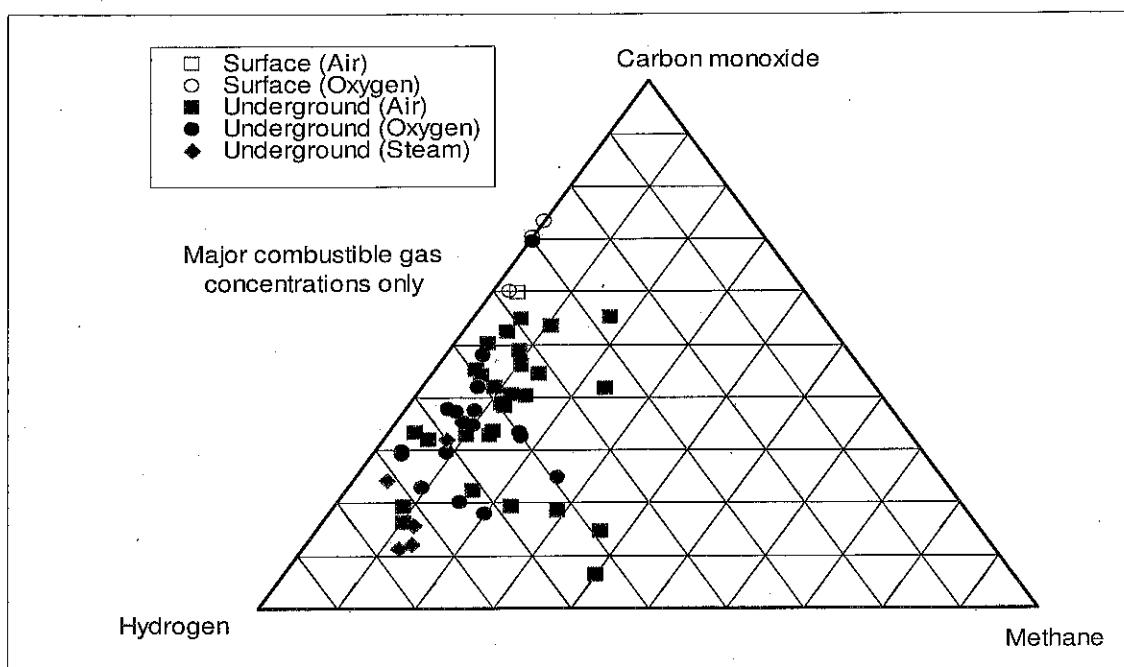


Figure 3: Product gas compositions from various gasification processes

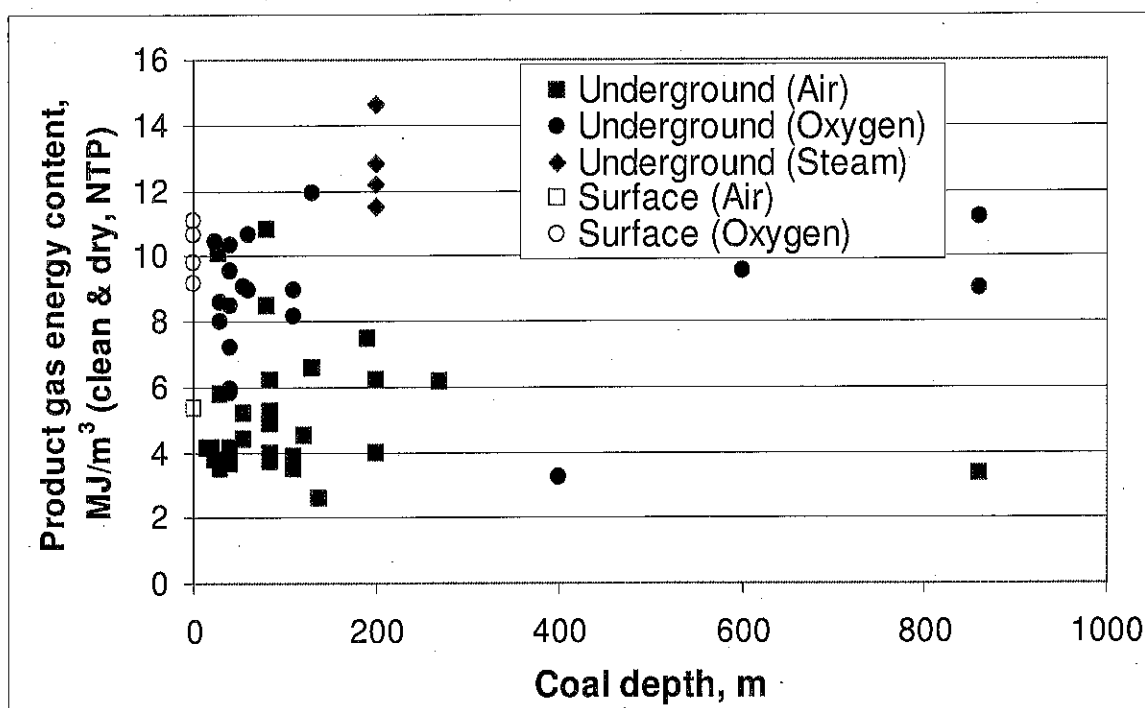


Figure 4: Product gas calorific value relative to coal seam depth

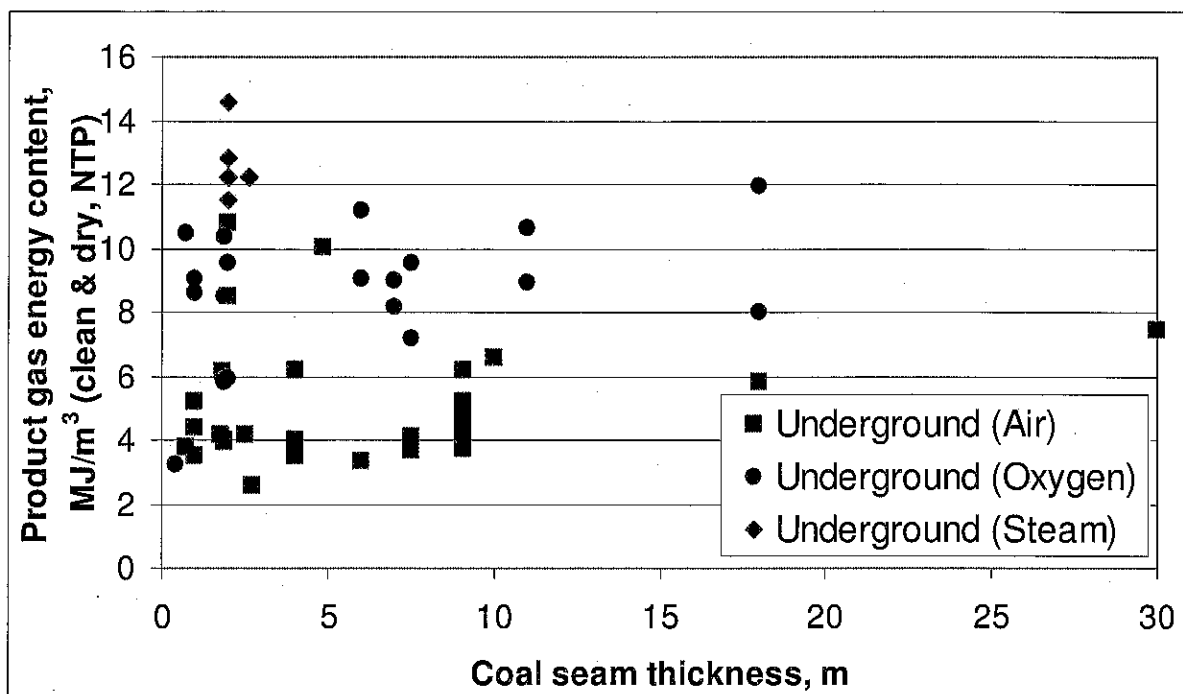


Figure 5: Product gas calorific value relative to coal seam thickness

Table 2: Product gas quality for selected underground and surface coal gasifiers

	CO %vol, dry	H <sub>2</sub> %vol, dry	CH <sub>4</sub> %vol, dry	CO <sub>2</sub> %vol, dry	N <sub>2</sub> +Other %vol, dry	Calorific value MJ/m <sup>3</sup> (dry, STP)
Underground gasification sites						
SDB Rawlins-2	15.7	31.0	16.4	35.5	1.4	11.83
VW (air) Pricetown	13.7	11.5	7.9	10.2	56.7	6.10
CRIP Thulin	23.0	14.0	17.0	29.0	17.0	11.15
VW (air) Angren	5.6	21.7	1.1	20.2	51.4	3.49
Surface gasifiers						
Shell Buggenum	64.6	27.2	0.0	1.5	4.2	11.08
Texaco Polk	43.8	33.2	0.1	15.5	8.4	9.15
Prentiss Puertollano	59.4	21.6	0.0	3.6	9.4	9.82
Destec Wabash	51.1	32.1	1.9	12.0	3.0	10.67
KRW (air) Pinon Pine	25.0	15.4	1.4	5.9	52.3	5.36

## Efficiency of operation

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 Centralla/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 6. 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.

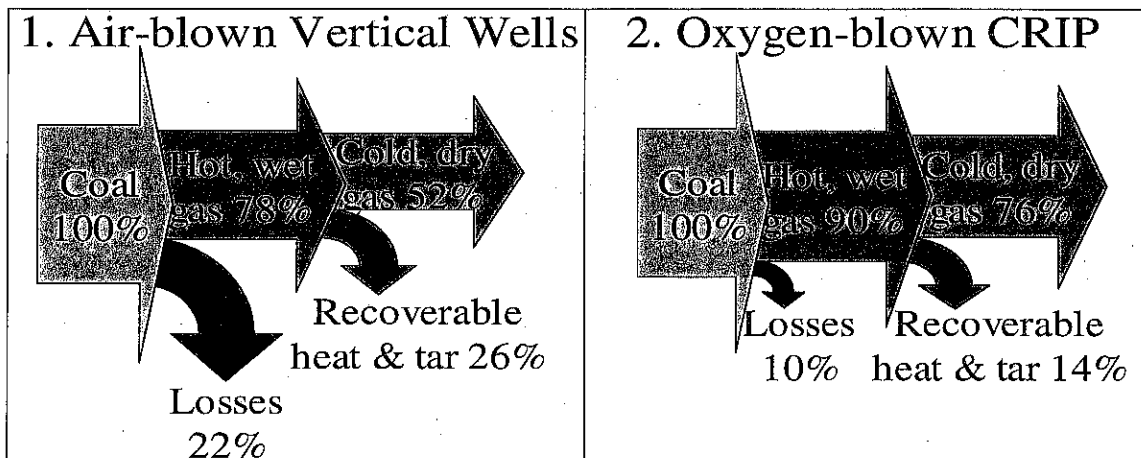


Figure 6: Energy flows in UCG processes: 1. Angren & 2. Rocky Mountain

## 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 gasifying 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<sup>18</sup> indicates that the ash content of the coal has a significant impact on the product gas quality, as shown in Figure 7. 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.

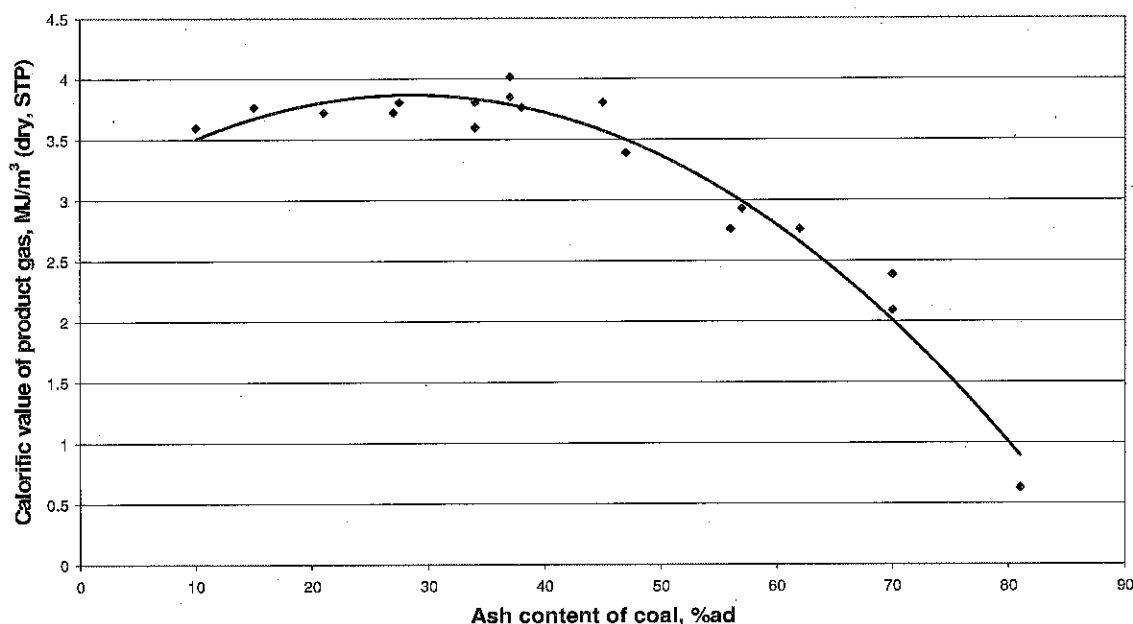


Figure 7: Impact of coal ash content on product gas quality<sup>18</sup>

### 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<sup>18</sup>. 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 8. 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.

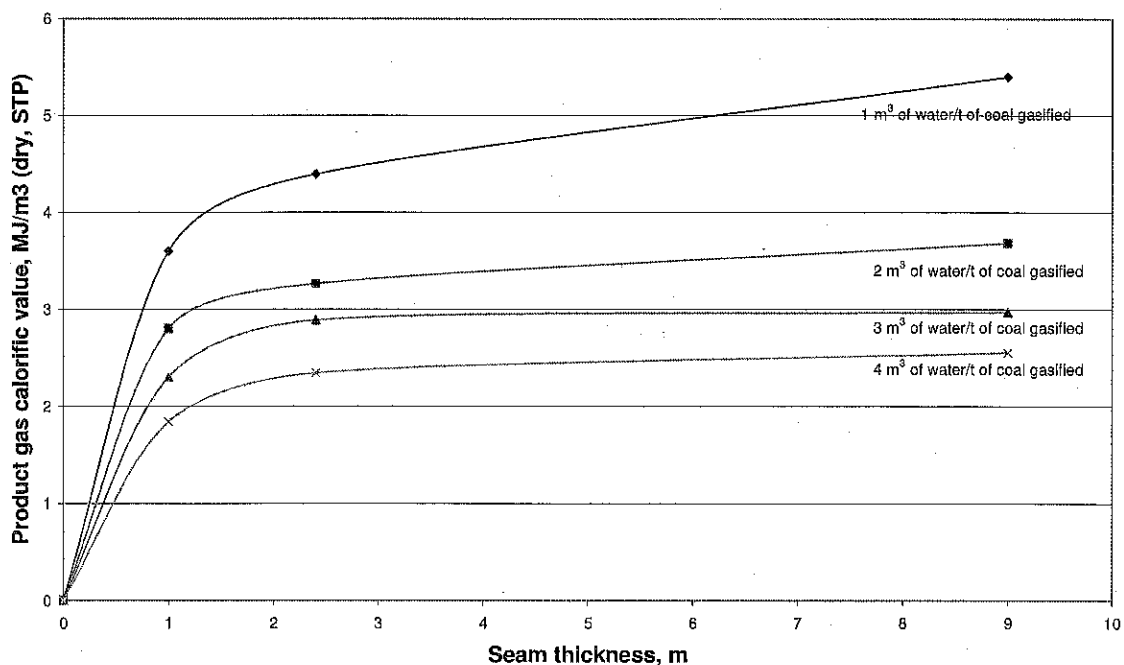


Figure 8: Impact of seam thickness and water ingress on product gas quality<sup>5</sup>

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<sup>18</sup>. 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 3, with both positive and negative site characteristics commented upon.



Table 3: Key factors to examine when determining the site potential for UCG operations

Item	Attribute	Comment
<b>COAL CHARACTERISTICS</b>		
Seam thickness	1m	Minimum feasible
	5m	Desirable minimum
	10m+	Optimal
Rank	Low to high	Not significant other than very low rank coals tend to have high moisture and very high rank tend to be difficult to ignite
Ash	<40% ad	Optimal
	40-60% ad	Up to 30% drop in performance
Strength	Sheared & weak	Can cause hole collapse and loss of drilling equipment
<b>GEOLOGY</b>		
Depth	200-400m	Best estimate as a trade-off between drilling economics, hydraulic head and gasification rates
Dip	0-20°	Optimal for most techniques
	20-50°	Problematical
	>50%	Limited to SDB techniques
Structure	Minimal faulting	Need to know seam position accurately and CRIP technique requires continuous seam
Intrusions	Dips/sills	Problematical to coal continuity
<b>GEOTECHNICAL</b>		
Immediate roof	Smooth & even caving	For controlled collapse into cavity
	Thermally stable	For controlled collapse into cavity
	Minimal permeability	To minimise water flow into cavity
Overburden	Caving limited	Minimise surface effects and gas loss
<b>HYDROLOGY</b>		
Hydraulic head	>200m	Optimal for maintaining water seal
Aquifers	High permeability	Can flood cavity
	Minimal permeability	Some water required for process
	Good water	Pose a contamination risk

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.

### **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.

### **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 be 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.

### **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.

### **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.

### **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.

### **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<sup>24</sup>. 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<sup>21</sup>. 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<sup>19</sup>, 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<sup>26</sup>, 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<sup>25</sup> 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<sup>22</sup>. 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 different mechanism for groundwater contamination can apply where strata deformation results in changed flow paths for groundwater. Covell and Thomas (1996)<sup>21</sup> determined that groundwater in a good water quality aquifer above the coal seam at Hoe Creek would be contaminated by organics to levels above the permissible limits for drinking water simply by coming into contact with unaltered coal, let alone gasification byproducts. While this form of contamination may be of lesser significance than that caused by gasification byproducts, it will still be of concern if the groundwater is used locally. It is likely that this finding is specific only to sites where there is a good quality aquifer close enough to the coal seam that deformation following coal extraction is sufficient to redirect flow of that aquifer into the coal seam, so this type of contamination will not be observed at many sites and sites with these conditions should be avoided.

### **Avoidance techniques**

A series of best management practices has been defined by the US EPA<sup>26</sup> 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<sup>22</sup>.

- 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<sup>23</sup>.

## **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<sup>23</sup>. 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<sup>27</sup>, 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<sup>3</sup>/hr for a 3 m thick coal seam and 5000-6000 m<sup>3</sup>/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<sup>3</sup>/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.



## 2. Analysis of a specific site

The performance of underground coal gasification is strongly linked to the characteristics of the specific site at which the operation is being performed and a detailed analysis of the proposed operation must be performed to ensure the financial and environmental viability. This is predominantly an intensive modelling exercise predicting the performance of not only the gasification process but also the hydrological and geotechnical behaviour of the site in response to gasification and simulation of the overall process, including utilisation of the UCG product gas. The overall design and operational performance can also be used to estimate the financial performance of the operation. A significant quantity of data is required about the site to allow for this comprehensive analysis to be performed. An example analysis has been prepared for a nominally 400MWe UCG combined cycle plant located at a specific site in the Eastern Surat Basin<sup>34</sup>. In this case the target coal seam for gasification is approximately 10m thick at 395m depth.

### Methodology

The analysis included:

- Selection and characterisation of a site expected to be suitable
- Design of the gasification plant.
- Modelling of the underground gasification process, geotechnical behaviour of the site (eg. subsidence) and hydrological flows including contaminant transport.
- Detailed process simulation of IGCC-style processes in various forms, such as a standard version without any carbon dioxide removal, a version with a simple carbon dioxide removal stage and a version with a shift reactor and carbon dioxide removal.
- All technologies considered are currently available on suitable scales.
- Two cases of differing UCG performance and a surface (Destec) gasifier were compared in the each of the process configurations.
- Costs of most plant items were sourced from a NETL analysis<sup>32</sup> with proportionality of cost to plant capacity assumed where the plant capacity required differed from the NETL case.
- Carbon dioxide removal and shift reactor costs were determined individually for the cases using established CSIRO methods.
- UCG plant costing was based on Australian drilling costs.
- A capacity factor of 85% was used for all plant configurations.
- An EPRI costing method was used to estimate the cost of electricity in the 10<sup>th</sup> year of operation.

Other assumptions:

- Water was assumed to be available in the required volumes for cooling. This is an issue with the shift reactor process in particular, as it has high cooling requirements.
- Organic by-product disposal costs/sale profits were taken as zero. There is a wide range of opinion on the worth of these by-products and a more detailed analysis will be necessary to determine the true commercial value.
- Site remediation costs were not included. With tight operating controls this is only likely to be significant after the plant has ceased operation or if geological discontinuities interfere with operations.
- Site characterisation (exploration) costs were not included.

### Site selection and plant design

A set of selection criteria for UCG has been generated by CSIRO and a geological model of the subject region (in this case the Eastern Surat Basin) was prepared to identify a site which matched the criteria. Due to the limited data for the region, the criteria were simplified to a search for an area with a thick coal seam at 300-400m depth and no good water aquifers above the seam. A site was selected with a coal seam of approximately 10m thickness at 395m depth. The plant design deemed suitable for UCG at this depth is based around modules using 4 directionally drilled injection wells, 3 directionally drilled production wells and 6 vertical wells for ignition and water control, arranged as shown in Figure 9. A pillar of 60m is specified between modules to ensure that connection of gas between modules does not occur.

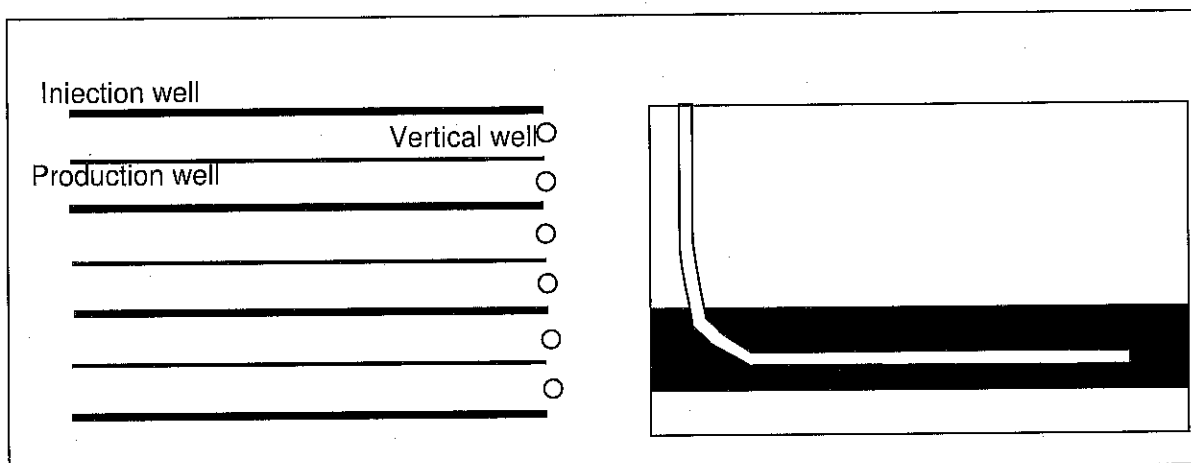


Figure 9: UCG module design

Spacing of the parallel wells selected for the design was 30m. It is difficult to specify the spacing on a purely theoretical basis and this figure is based on a fairly conservative interpretation of past results that is aimed at ensuring that adequate control can be maintained. 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. 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.

General methods for estimating drilling cost are detailed by Mitchell<sup>31</sup>. A specific design and costing case study for both the vertical and directionally drilled wells constructed for the Rocky Mountain 1 UCG trial is given by Logan<sup>30</sup>. Based on these studies, in conjunction with local equipment and materials costs, it is possible to provide approximate cost estimation formulae for drilling, casing and lining both vertical and directionally drilled wells suitable for UCG operations. It is difficult to produce accurate values due to the previously stated site variations and also the unusual nature of the wells, so local drilling companies are unsure of the costs involved in some aspects of the construction process and can provide only generic estimates without testing at the specific site. There are two different types of drilling that are used in constructing an underground coal gasifier, namely vertical and directional (also termed horizontal). The costs of either of these will be influenced by the site characteristics and directional drilling can be drastically affected by coal structural properties. In addition, the diameter of the wells has a

large effect on the drilling cost and this will typically be influenced by the pressure of operations and the use of either oxygen or air. The components that comprise the majority of the cost of drilling are the acquisition of drilling equipment, the time taken to drill and case the hole and the cost of drilling mud. Minor costs involved are the casing and lining materials and cement for sealing the casing in place. Abnormal costs can be incurred and increase the cost for a specific hole significantly, with a specific example being the requirement to 'fish' to recover a trapped drilling motor if the hole collapses when drilling directionally in-seam. Therefore, any estimate of cost for an individual well will be subject to a substantial error that will be assumed to average out over a large number of drilling operations. However, if the site proves to be difficult to drill, there is the potential for significant error in the economics that should be considered.

For directionally drilled wells, well construction involves drilling, casing and cementing a large diameter vertical section, termed the head section, to approximately 10m depth. This acts essentially as a foundation for further drilling. A smaller diameter vertical section is then drilled, cased and cemented to a depth termed the kick-off point, below which a down-hole drilling motor is used to drill a medium radius curved hole until the desired depth in the coal seam is reached. The hole up to this point is termed the build section and is cased and cemented before a smaller drilling motor is inserted to drill the in-seam hole through the coal seam. Depending on the well requirements, the in-seam distance can be either left as an open or lightly cased hole for production duty or has a continuous liner inserted without cementing for injection duty.

For vertical wells, the head section is constructed and the vertical cased and cemented section extended downwards until it is at the desired depth in the coal seam. Costing data for each section are given in Table 3, with all costs being in approximate 2003 Australian dollars. For other hole sizes, the drilling cost is approximately proportional to the cross sectional area ratio to the power of 0.7 for a particular type of drilling, the casing or liner cost is approximately proportional to the diameter and the cementing cost is estimated by the volume that must be filled between the hole and casing. The basic drilling costs were sourced from different Australian drilling companies, notably Mitchell's Drilling for directional drilling. Casing and cementing costs were adapted from Logan<sup>30</sup>.

Table 4: General costs for UCG well construction

Section	Hole diameter mm	Casing diameter mm	Drilling cost \$/m	Casing & cementing cost \$/m
Head	374.7	298.5	603.7	52.4
Vertical	250.8	193.7	363.4	27.8
Build	250.8	193.7	726.8	27.8
Horizontal	155.6	127.0 (Liner)	214.3	-

The total cost of constructing the UCG module described above is approximately \$3.471 million. Mitchell<sup>31</sup> recommends that an error of +/-30% in the cost estimate be assumed for one-off well construction, however for multiple wells at the same site the cost should approach the average cost as experience optimises the construction process. Therefore, the estimated cost will be taken as \$3.471 million per module.

## Modelling UCG performance

In order to estimate the size and performance of plant items it is necessary to predict the performance of the UCG site, in particular the product gas flow and composition for a module. A complex 3D model of UCG has been developed by CSIRO to predict cavity growth rates and assist in UCG layout development, however, in this application it is more suitable to use a simpler model that uses a mixture of theory and empirical relationships based on the geological conditions and the feed materials. This model is essentially an expanded mass and energy balance for the system with heat losses estimated from the different site characteristics and operating conditions. Additional material on modelling methods in UCG is given in presentation form in Section 4.

The key variables in the model are pressure, exit gas temperature, oxygen and water flow rates per mass of coal gasified and the coal seam characteristics. An assumption used is that the gas will be at equilibrium composition at the exit of the gasifier as if it was at a temperature of 800°C, despite the actual gas temperature being lower than this. This is based on an examination of experimental results from numerous UCG trials and the assumption of equilibrium is suitable for a large scale UCG cavity as the endothermic heterogeneous and homogenous reactions in a gasifier tend to slow as the temperature drops and the composition will remain approximately constant as the gas cools. Another assumption is that 15% of the affected coal (daf basis) is left as char, which is an average figure based on prior UCG experience and other CSIRO modelling. The quantity of residual char will be largely determined by the accuracy of drilling, as it will be the result of the wells being placed significantly above the floor of the coal seam. The water influx from the surrounding rock is estimated from site hydrological modelling. The quantity of oxygen required is determined based on an energy balance for the system with a correction for heat losses. The heat loss estimation method is derived from work published by Skafa<sup>33</sup> and Olness and Gregg<sup>8</sup> regarding the change in product gas quality with changing site and operating conditions. The key findings in these studies were that gas quality, which relates to heat loss in this case, varies in inverse proportionality to seam thickness and gas volume flow. This observation matches theory well, as the heat loss will be determined largely by the roof area per unit volume of coal with enhancement caused by increased heat transfer coefficient at high gas flow velocities.

Using the described model, two UCG scenarios were developed to give a conservative range of potential operational characteristics for the selected UCG site. These were designated as Good and Bad UCG cases, with the Good case being an estimate of the expected behaviour and the Bad case being artificially modified to be an extreme case of poor performance. Some characteristics of these cases are given in

Table 5, along with the same data for a published study on a Destec entrained flow gasifier from NETL<sup>32</sup> that will be used as a base for comparison in the study. There are some significant compositional variations between the Destec and UCG product gases and the UCG gases have a significant disadvantage in energy density, which has ramifications regarding performance in conventional gas turbines.

Table 5: Characteristics of the clean fuel gas and preparation for IGCC case studies

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

### Process simulation

In order to evaluate the overall performance, then plant sizing and costing, of the process incorporating the UCG plant an overall simulation of the process must be performed. The simulations of the processes incorporating the UCG site was prepared in the HYSYS.Process simulation package and the performance of the process components set to match the published output. Additional information on power process simulation is given in presentation form in Section 4. 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<sup>32</sup>. This is a fairly standard IGCC process using existing technologies, such as a fuel gas quench followed by cold gas cleaning and sulfur removal. This process design was selected because it utilises currently available technologies that are also suitable for the processing of UCG product gas. This allows that alternate configurations can be simulated using the same equipment performance characteristics for both UCG and Destec sourced fuel gas, 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 plant specification with regard to temperature, pressure and mass flow rate. The differences in the composition of the three product gases in Table 1 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 this analysis; 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

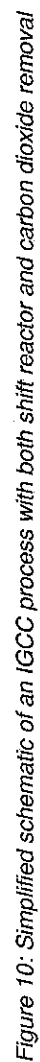
second is a configuration termed IGCC-CO<sub>2</sub>, which is a modification of the IGCC process that includes extra plant for the removal of 90% of the carbon dioxide present in the fuel gas. The third configuration is significantly more complex and incorporates two water-gas shift reactors (high and low temperature) before removal of 90% of the carbon dioxide, with this being termed the IGCC-Shift process. A simplified process diagram for this third case is shown in Figure 10. 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. A major problem is that, for the cases with carbon removal, the elevated hydrogen content in the fuel gas is likely to hinder the performance of the gas turbine system. The carbon dioxide removal plant and shift reactors were not considered in the NETL study<sup>32</sup>, so the plant sizing was determined by CSIRO Energy Technology staff using established models and a standard Selexol plant design for carbon dioxide removal and a 2-stage high and low temperature shift reactor system for the carbon monoxide to carbon dioxide shift. These are existing technologies and are therefore not as optimistic as some other published results that incorporate innovative technologies that have not yet been used on a large scale.

A summary of the power generation and consumption in each of the case studies is given in Table 6, along with the Greenhouse emissions per unit of net output. 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<sup>32</sup> and it can be seen in the table that these constitute a very minor part of the overall energy flows.

Table 6: Summary of IGCC configuration characteristics

<b>IGCC</b>	<b>Destec</b>	<b>Good UCG</b>	<b>Bad UCG</b>
Steam turbine output, MW <sub>e</sub>	174.8	122.7	123.0
Gas turbine output, MW <sub>e</sub>	513.8	517.3	517.1
Compressor usage, MW <sub>e</sub>	237.1	241.4	250.3
Generator losses, MW <sub>e</sub>	6.5	5.8	5.8
Oxygen plant, MW <sub>e</sub>	26.0	26.3	34.4
Major pumps, MW <sub>e</sub>	2.0	2.1	2.1
Heating/Cooling, MW <sub>e</sub>	8.2	9.2	10.3
Auxiliary, MW <sub>e</sub>	8.2	5.6	5.6
CO <sub>2</sub> Shift & Remove, MW <sub>e</sub>	0.0	0.0	0.0
Net power output, MW <sub>e</sub>	400.6	349.7	331.5
CO <sub>2</sub> emissions, t/MWh	0.644	0.814	0.926
<b>IGCC-CO2</b>	<b>Destec</b>	<b>Good UCG</b>	<b>Bad UCG</b>
Steam turbine output, MW <sub>e</sub>	173.9	119.0	119.9
Gas turbine output, MW <sub>e</sub>	515.8	523.3	524.6
Compressor usage, MW <sub>e</sub>	238.4	245.3	255.1
Generator losses, MW <sub>e</sub>	6.5	5.8	5.8
Oxygen plant, MW <sub>e</sub>	26.0	26.0	34.2
Major pumps, MW <sub>e</sub>	2.0	2.0	2.0
Heating/Cooling, MW <sub>e</sub>	7.2	6.1	6.5
Auxiliary, MW <sub>e</sub>	8.2	5.6	5.6
CO <sub>2</sub> Shift & Remove, MW <sub>e</sub>	15.0	8.7	11.4
Net power output, MW <sub>e</sub>	386.5	342.7	323.9
CO <sub>2</sub> emissions, t/MWh	0.580	0.511	0.521
<b>IGCC-Shift</b>	<b>Destec</b>	<b>Good UCG</b>	<b>Bad UCG</b>
Steam turbine output, MW <sub>e</sub>	64.6	73.6	77.4
Gas turbine output, MW <sub>e</sub>	546.7	537.7	538.6
Compressor usage, MW <sub>e</sub>	253.7	252.2	262.8
Generator losses, MW <sub>e</sub>	5.1	5.2	5.2
Oxygen plant, MW <sub>e</sub>	29.6	27.7	36.3
Major pumps, MW <sub>e</sub>	2.1	2.1	2.1
Heating/Cooling, MW <sub>e</sub>	15.3	19.7	21.3
Auxiliary, MW <sub>e</sub>	7.8	5.3	5.4
CO <sub>2</sub> Shift & Remove, MW <sub>e</sub>	32.4	26.6	29.0
Net power output, MW <sub>e</sub>	265.3	272.6	253.8
CO <sub>2</sub> emissions, t/MWh	0.149	0.328	0.338





## Production economics

The economic modelling of UCG has been aimed at determining if development of UCG is feasible and, as the product gas is not directly saleable, requires that the process using the product gas be incorporated in the analysis. The analysis also accounts for any differences in the quality of the product gas compared to conventional sources. The accuracy of the analysis is not likely to meet the investment criteria of major companies and is indicative only. There are obvious difficulties in producing realistic and acceptable assessments for UCG, with some of the major issues being:

- UCG technology is novel and has not previously been applied in true commercial operations;
- Any analysis is site specific and, whilst some verification of model performance has been attempted, experimental verification of the site performance is recommended prior to design of a large installation;
- UCG does not produce something which is directly saleable, so will typically be heavily integrated with another plant that produces electricity or chemicals. This adds a level of complexity and risk to the analysis, as detailed plant performance and costing data are limited for proprietary plant designs; and
- There are many different economic analysis techniques with most corporations having variations of these that are adapted to their particular financial structure.

The following section is based on the approach used for a case study prepared for the CSIRO Energy Transformed Flagship for electricity generation from UCG. The costing was performed in a fairly rigorous manner, but it should be noted that the key objective of the study was to analyse the environmental impacts. Other cost analyses have been prepared on a generic basis for electricity generation and liquid fuel synthesis, but these are relatively inaccurate due to the lack of a specific site and simplifying assumptions used in the process simulation.

In Table 7 a summary of the capital and operating costs for the different plant configurations is given, as estimated from the data in NETL<sup>32</sup> and with supplementary input for UCG costs and carbon dioxide removal costs. The core plant items have been costed assuming that cost is directly proportional to the sizing or duty estimated from the process simulation analysis and related to the NETL costs. Where necessary, costs have been converted from US currency using the method described in Graham *et al.*<sup>29</sup>, 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. A capacity factor of 0.85 has been applied to all cases.

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. These advantages for UCG offset the lower power output for the UCG processes that arises mostly from reduced steam production when considering cost per unit of production.

Table 7: Summary of costs associated with the IGCC configurations

<b>IGCC</b>	<b>Destec</b>	<b>Good UCG</b>	<b>Bad UCG</b>
<b>CAPITAL COSTS (A\$million)</b>			
Air separation	46.622	47.153	61.723
Gasification system	111.998	10.413	10.413
Gas processing	26.435	32.180	36.649
Gas turbine system	77.337	77.337	77.337
Steam plant system	48.810	42.489	42.979
Other plant	69.402	69.402	69.402
Total Capital (including on-costs)	568.287	412.84	441.921
Capital A\$/kW	1419	1180	1333
<b>OPERATING (A\$million/yr)</b>			
Coal	28.482	2.087	2.250
Drilling	0.000	1.637	1.766
Labour & Maintenance	17.220	17.220	17.220
Other	2.707	1.720	1.760
Credits (Sulfur & Tars)	0.000	0.000	0.000
Total Operating (Net)	48.409	22.664	22.996
Levelised electricity cost (10 <sup>th</sup> year, A\$/MWh)	43.90	32.10	35.74
<b>IGCC-CO2</b>	<b>Destec</b>	<b>Good UCG</b>	<b>Bad UCG</b>
<b>CAPITAL COSTS (A\$million)</b>			
Air separation	46.615	46.662	61.242
Gasification system	111.809	10.413	10.413
Gas processing	92.171	52.368	56.860
Gas turbine system	77.337	77.337	77.337
Steam plant system	48.418	41.437	41.468
Other plant	69.402	69.402	69.402
Total Capital (including on-costs)	665.560	440.670	469.114
Capital US\$/kW	1722	1286	1448
<b>OPERATING (A\$million/yr)</b>			
Coal	28.434	2.071	2.230
Drilling	0.000	1.625	1.750
Labour & Maintenance	18.295	17.660	17.662
Other	2.705	1.718	1.757
Credits (Sulfur & Tars)	0.000	0.000	0.000
Total Operating (Net)	49.434	23.075	23.399
Levelised electricity cost (10 <sup>th</sup> year, A\$/MWh)	50.86	34.09	37.94
<b>IGCC-Shift</b>	<b>Destec</b>	<b>Good UCG</b>	<b>Bad UCG</b>
<b>CAPITAL COSTS (A\$million)</b>			
Air separation	53.072	49.730	65.179
Gasification system	127.409	10.413	10.413
Gas processing	87.713	84.919	90.960
Gas turbine system	77.337	77.337	77.337
Steam plant system	34.911	35.708	36.269
Other plant	69.402	69.402	69.402
Total Capital (including on-costs)	671.670	485.387	518.231
Capital A\$/kW	2532	1781	2042
<b>OPERATING (A\$million/yr)</b>			
Coal	32.401	2.202	2.364
Drilling	0.000	1.728	1.855
Labour & Maintenance	18.181	18.087	18.108
Other	2.883	1.736	1.776
Credits (Sulfur & Tars)	0.000	0.000	0.000
Total Operating (Net)	53.465	23.752	24.103
Levelised electricity cost (10 <sup>th</sup> year, A\$/MWh)	76.48	47.01	53.24

### **Additional costing issues**

**Water** - 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.

**Organic by-products** - UCG product gas contains significant quantities of condensable organic compounds that will be removed in the gas cleaning process into the scrubber water. The economic analysis does not include any post-treatment of the contaminated water, so this is implicitly considered a zero cost process. There is a wide range of opinion on the economic worth of the organic components, with contrasting opinions of the material as a hazardous waste, an additional fuel that can be reformed to fuel gas or a source of valuable chemicals. There are certainly valuable components in the by-product, but the cost effectiveness of processing to extract these and the availability of customers are uncertain. Informal advice from a company involved in processing of similar materials is that they generally take this type of material, but will not pay for it due to the processing costs they incur. For this reason it was assumed that the no net cash flow would arise from the by-products.

**Site characterisation** – The initial exploration costs involved in characterising the UCG site to the degree of accuracy necessary have not been included. Some internal discussion has occurred regarding the accuracy required and the best techniques, but costing has not been performed.

**Site remediation** - It is relatively uncommon for decommissioning and remediation costs to be considered in this type of costing analysis, however it is becoming more likely that this type of inclusion will be necessary in the licensing of new plants. The environmental analysis performed by CSIRO considers the control of groundwater contamination and closure of UCG modules, however this was not costed separately. During plant operational life it is likely that much of the cost of decommissioning exhausted modules will be absorbed into normal operational costs and it will only be if significant volumes of groundwater are affected after plant closure that the costs may become significant. There is little published data on this type of remediation work and there is also uncertainty as to the requirements that will be imposed by regulators.

### **Financial modelling**

The NETL study<sup>32</sup> used a standard method developed by EPRI to estimate the cost of electricity from the power plant during the 10<sup>th</sup> year of operation, assuming a 20-year plant life. This method is published in the Technical Assessment Guide by EPRI and is updated periodically to reflect changes in plant operations and costing. The general basis of the method is to multiply the various types of cost involved in the process by levelising factors and sum the results, so that a cost of electricity estimate is produced. In constant currency terms, the levelising factors are 0.148 for capital costs, 0.948 for coal cost and 1.000 for all

other operating costs. A summary of the levelised costs for each of the systems is given in Table 8 along with the Greenhouse emissions, as this needs to be considered to make the costs meaningful.

*Table 8: Levelised electricity costs and GHG emissions for the Destec and UCG systems*

Process	Destec		Good UCG		Bad UCG	
	Cost AU\$/MWh	GHG t/MWh	Cost AU\$/MWh	GHG t/MWh	Cost AU\$/MWh	GHG t/MWh
<b>IGCC</b>	43.90	0.644	32.10	0.814	35.74	0.926
<b>IGCC-CO2</b>	50.86	0.580	34.09	0.511	37.94	0.521
<b>IGCC-Shift</b>	76.48	0.149	47.01	0.328	53.24	0.338

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 from Table 8. 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 as in the Bad UCG case. 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, if any. 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.

In summary, the process option with UCG and carbon dioxide removal appears to be a cost effective method of reducing Greenhouse emissions. Further reduction using shift reactors has limited effectiveness in the UCG case, but is the obvious approach in the case of the Destec system as carbon dioxide removal alone is ineffective. As neither approach analysed removes methane, a more complex process with reforming of methane to fuel gas would be required for UCG to be considered in a 'zero' emission role.

## **Extent and significance of environmental impacts**

### **Summary**

The analysis of the extent and significance of environmental impacts of UCG were examined using a single case study for the operation of a nominally 400MWe power plant in the Eastern Surat Basin. The site was selected based on analysis of a geological model of the region that had been developed from publicly available exploration data. The design of a suitably sized UCG plant was developed from a model based evaluation of the likely behaviour of the site under gasification conditions. The environmental analysis, with concise observations, can be summarised as:

- Greenhouse emissions estimates were based on a process simulation for an IGCC-style process using the product gas, which incorporated the potential use of carbon dioxide removal and shift reaction with carbon dioxide removal to reduce the Greenhouse emissions. Some process options, namely the use of carbon dioxide removal, appear to provide a good combination of reasonable cost and reduced Greenhouse emissions for UCG processes. The standard IGCC process considered is not particularly suited to the UCG product gas due to poor gas turbine characteristics, however newer types of turbine (which could not be accurately simulated due to a lack of data) are likely to improve on this performance.
- Local geotechnical modelling was performed to evaluate the likely subsidence and hydrological changes caused by operation of the site. Subsidence does not appear to a significant problem due to the insensitive nature of the land use. Groundwater usage is unlikely to have any significant impact, other than directly over the site.
- Regional hydrological modelling examined the wider impact of water usage and the potential for spread of contaminants from the site both during and after operations. If contaminants are generated in significant quantities the hydrological changes at the site have the potential to distribute them into overlying aquifer systems. There was no attempt to model the attenuation of the contaminants due to reaction or adsorption processes, but dilution alone will reduce the concentrations rapidly to levels that are likely to only be an issue if good quality groundwater is present. There is a lack of clarity in the regulation of groundwater contamination that will require negotiation of limits for groundwater that is lower than drinking water quality but is suitable for agricultural use.

The likely environmental impacts of UCG were considered to be acceptable under current legislation and the process has some advantages over conventional plants. However, it is recommended that UCG should not be used at sites where good quality groundwater is present above the coal seam to minimise the potential for contaminating useful water resources.

### **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 modelling 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.

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. The methodology and results for the costing were discussed in a previous section. A summary of the Greenhouse emissions and costing for different process configurations is given in Figure 11, with the column data being from this study and some additional values given for other plants from a CCSD study<sup>36</sup> and Linc Energy publications based on the Chinchilla trial results. The validity of directly comparing the financial analysis results of these studies is uncertain, but one observation of note is that the natural gas case used a gas cost of \$3.50/GJ. The UCG-CO<sub>2</sub> cases from this study are highlighted as being of significance due to the combination of moderate cost and moderate Greenhouse emissions. Note that carbon dioxide sequestration costs were not considered in this study and are expected to add approximately \$3-4/MWh if a convenient storage site can be located.

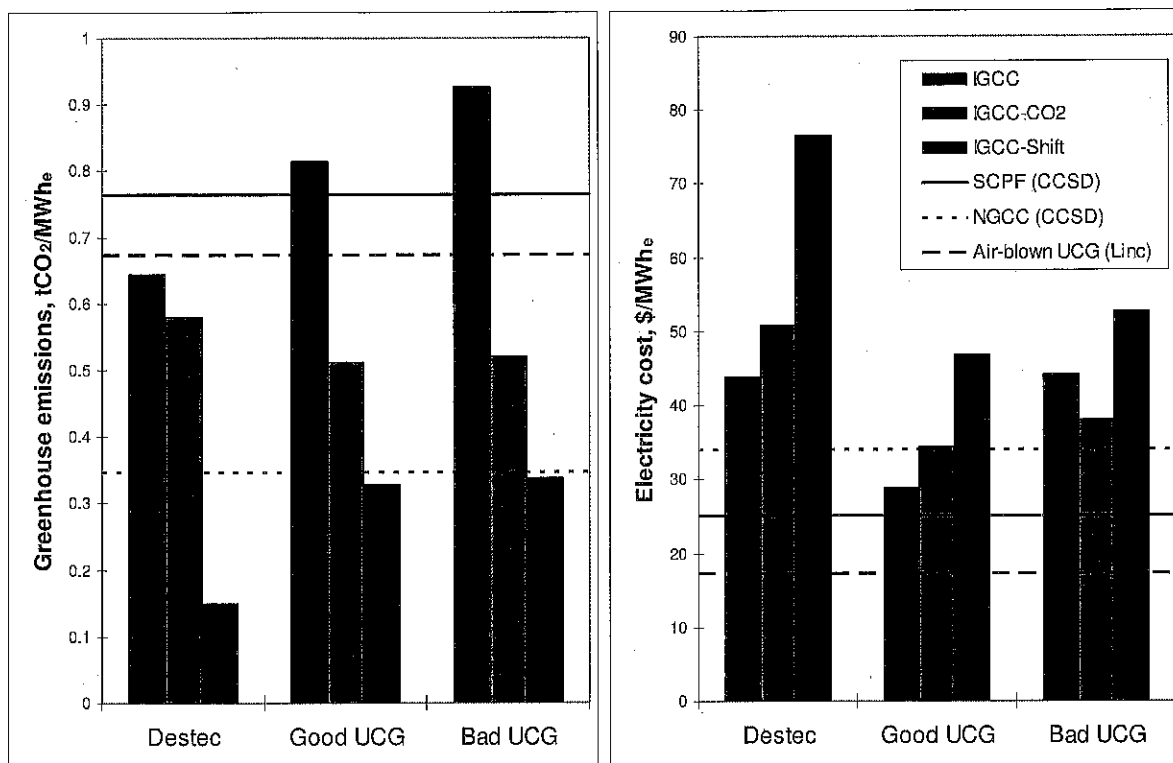


Figure 11: Greenhouse emissions and electricity cost for different process configurations

### 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<sup>35</sup>. 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. Modelled 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 are 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 are 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.

A summary of predictions from the modelling is given below. In Figure 12, the predicted subsidence directly above the UCG modules is shown, with the maximum being approximately 0.5m. This is unlikely to be of any significance at the site, given that the land is used only for forestry or light grazing.

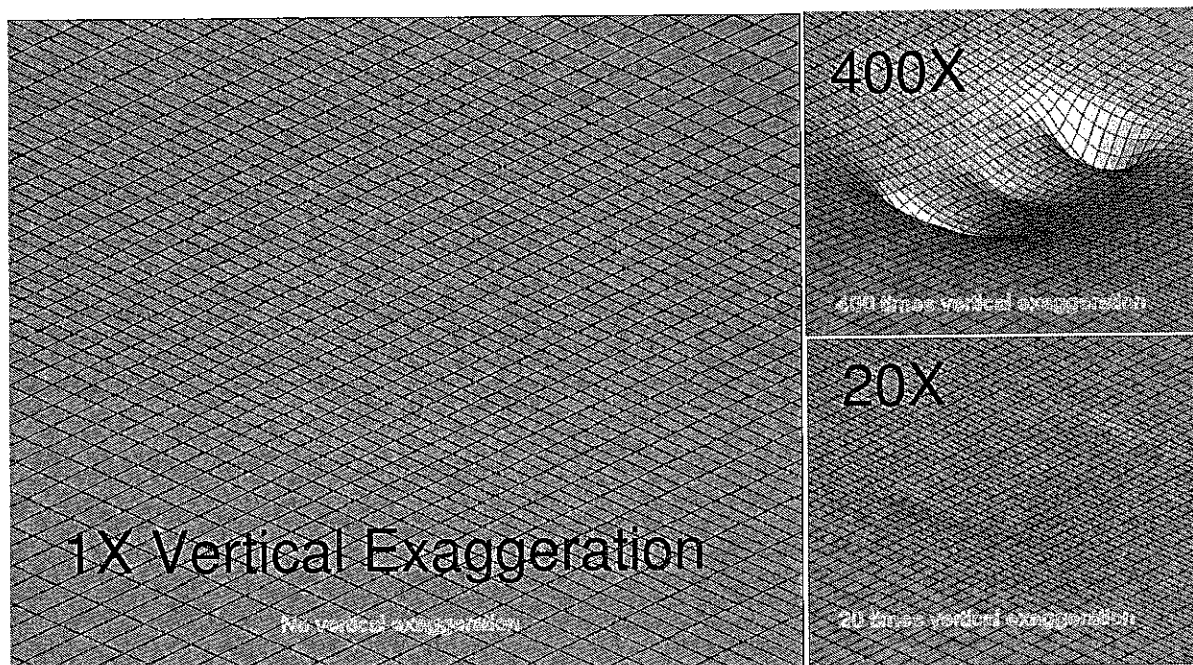


Figure 12: Subsidence directly above the UCG modules

In Figure 13, the predicted changes in the water table height resulting from the UCG operation are shown. The indicated extent of the impact is has an approximately 10km diameter with the boundary being a 0.5m drawdown, which is generally regarded as insignificant. The maximum drawdown is 17m directly above the site. One of the reasons for the selection of a deeper coal seam for UCG is explained in this, as a 17m decrease in head is relatively insignificant in a total hydrostatic head of over 300m whereas it is significant in shallow sites. Therefore, there is little disturbance to UCG operations in this drawdown. In terms of environmental impact, the groundwater was predicted to return to normal levels within 2 years after UCG operations ceased so impact is temporary. Groundwater usage by UCG will typically be lower than other resource extraction techniques at the same site. For example, coal seam methane extraction requires that the coal seam be pumped out to free the methane and underground mining requires dry working conditions with the mine operating at atmospheric pressure, not the higher pressures of UCG.



Figure 13: Drawdown of the groundwater around the UCG site

Prediction of groundwater contamination is more complex as it requires assumptions to be made regarding the efficiency of environmental controls during operation and the performance of the shutdown procedures in removing residual contaminants. Obviously, if this is done well there will be no contamination of groundwater and it has only been a few UCG sites where contamination has occurred to levels that would be a concern. The UCG cavities in this case were assumed to be full of significantly contaminated water, with contamination being elevated dissolved salts and an organic source material that leaked benzene at a constant rate indefinitely. Benzene was selected for the analysis as it is a fairly mobile organic that has been present in significant quantities in groundwater at contaminated UCG sites.

In Figure 14, the predicted distribution of dissolved salts is shown at the maximum spread of a significant concentration above the background levels. There is not a significant impact as the salts disperse to background levels quite rapidly and the region of influence extends only marginally outside the UCG cavity.

In Figure 15, the spread of benzene 100 years after operations ceased is shown in the aquifer above the coal seam. Note that was no provision for reaction or adsorption of the benzene in the modelling due to the uncertainties involved and the release was maintain at a constant rate in the cavities, so this is essentially a maximum impact bound that would not be attained in practice. There has been a significant dilution of the benzene, the spread has been quite slow and the levels indicated would not be of great concern given the poor quality of the water in the aquifer. These predictions do highlight that the use of UCG near good quality aquifers is ill-advised. For a more accurate analysis additional research would be required into the breakdown rates of organics in the different geological strata at the site. A literature review of the topic revealed a considerable range of breakdown rates at different sites, depending on the chemical and biological conditions.



Figure 14: Distribution of elevated dissolved solids in groundwater

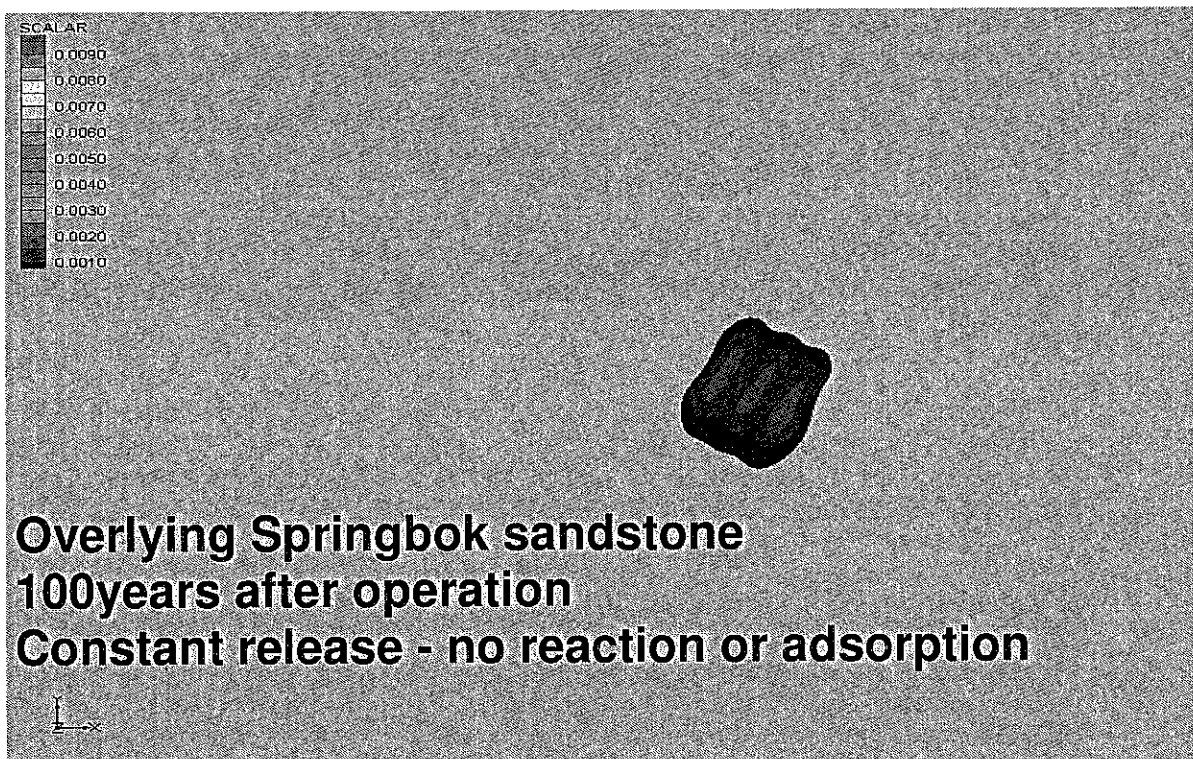


Figure 15: Distribution of elevated organics in groundwater

### Conclusions from the analysis


The predictions produced during the example analysis are only valid for the specific site that was selected and characterised for the study. 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 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.

### 3. Tutorial on UCG





**Tutorial on Underground Coal Gasification (UCG)**

Dr Andrew Beath CSIRO Exploration & Mining Australia	Dr Cliff Mallett Carbon Energy Pty Ltd Australia
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Supported by the Australian Government through the  
Asia Pacific Partnership (AP6) Coal Mining Task Force

This tutorial is intended to give a broad overview of UCG technologies and the current capabilities in predicting performance of UCG-based processes.

 **Tutorial outline** 

**Session 1:**

- o Introduction
- o Fundamentals & UCG design

**Session 2:**

- o Behaviour prediction
- o Process performance & economic viability


**Session 3:**

- o Groundwater & surface impacts
- o Site selection & characterisation
- o Social perceptions



**Session 4:**

- o Case study
- o Discussion

## Session 1A: Introduction





**Session 1A: Introduction**



 <b>Dr Andrew Beath</b> CSIRO Exploration & Mining Australia	 <b>Dr Cliff Mallett</b> Carbon Energy Pty Ltd Australia
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Supported by the Australian Government through the Asia Pacific Partnership (AP6) Coal Mining Task Force


The tutorial is based largely upon expertise developed in CSIRO during a long-term research project that culminated in the launch of a joint-venture spin-off company (Carbon Energy) that now owns the rights to commercially utilise that knowledge.

 **Introduction – Dr Andrew Beath** 


**Dr Andrew Beath is a chemical engineer with a varied range of experience in industry and research. Over the last 7 years he has developed models to predict the growth of UCG cavities and the product gas properties, as well as simulation of processes which could utilise the product gas.**

 **Introduction – Dr Cliff Mallett** 

**Dr Cliff Mallett is a geologist with a long and varied career in research. Until recently he was Deputy Chief of CSIRO Exploration and Mining, where he initiated the research programme into underground coal gasification. He is now Executive General Manager of Carbon Energy, a company launched to commercialise the outcomes of CSIRO's UCG research.**



**Research background**

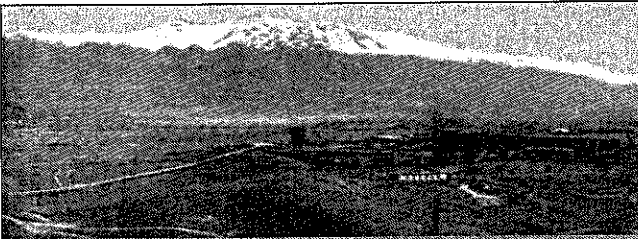



The CSIRO UCG research programme commenced in 1998. The major outcome has been a series of models and methodologies for:

- o Site characterisation
- o Cavity growth and gas production
- o Geotechnical behaviour
- o Hydrogeological flows
- o Overall process performance


The rights to commercial use of these are now owned by Carbon Energy.

## Session 1B: Fundamentals





**Session 1B: Fundamentals**

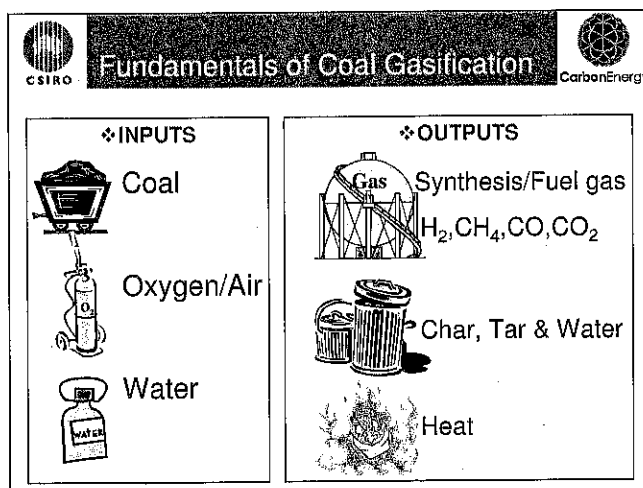


Dr Andrew Beath  
CSIRO Exploration & Mining  
Australia

Dr Cliff Mallett  
Carbon Energy Pty Ltd  
Australia

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This section covers the basic reactions that occur in UCG and the expected behaviour of UCG sites.







## Characteristics of UCG



❖ Underground coal gasification is like other coal gasification techniques, except that the geological strata form the reaction vessel.

❖ This adds a level of complexity to analysis of the behaviour of the process and leads to extra uncertainty due to the geological environment.



## A simple guide to UCG



UCG can be condensed to two areas of analysis that are indicated on the next two slides:

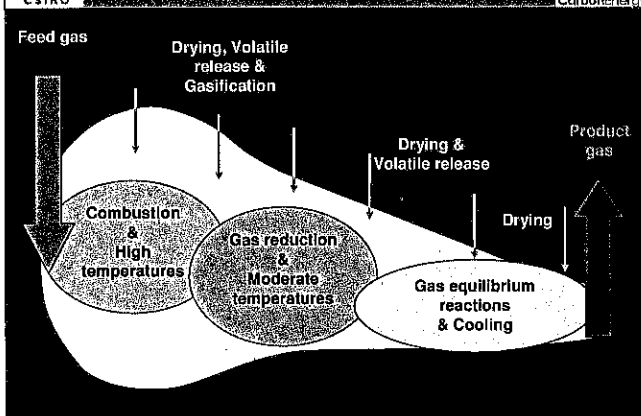
❖ Reaction processes

❖ Physical site changes

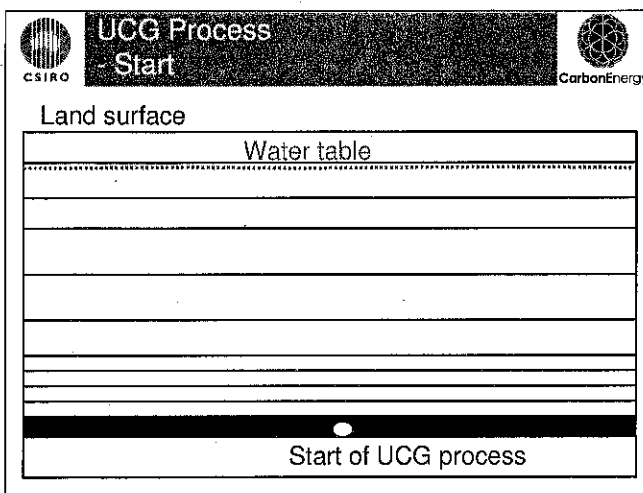
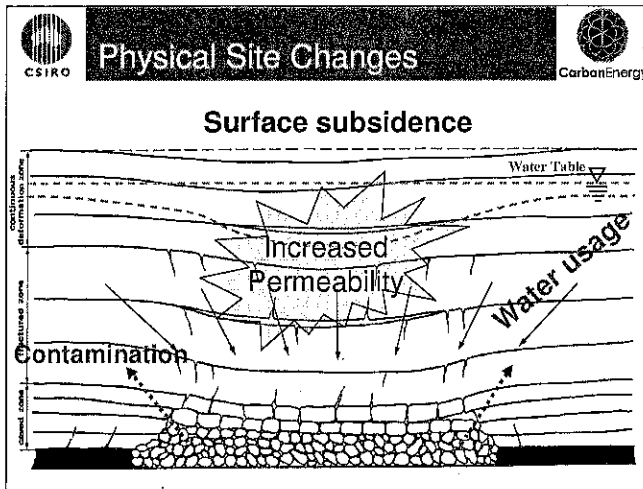
Each can be considered separately, but it is interaction of these that makes UCG analysis complex.



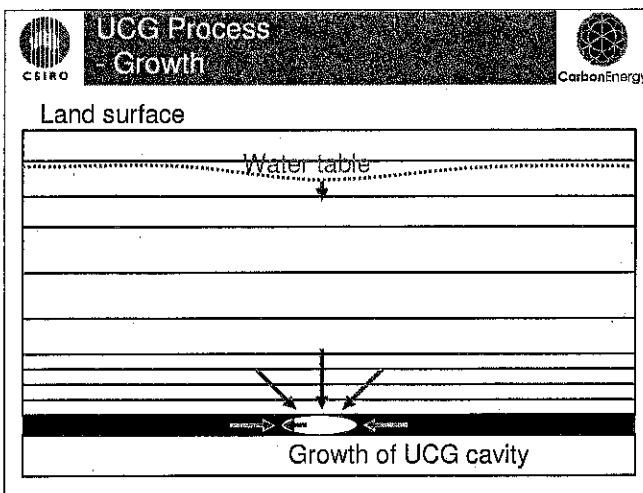
## Reaction Processes



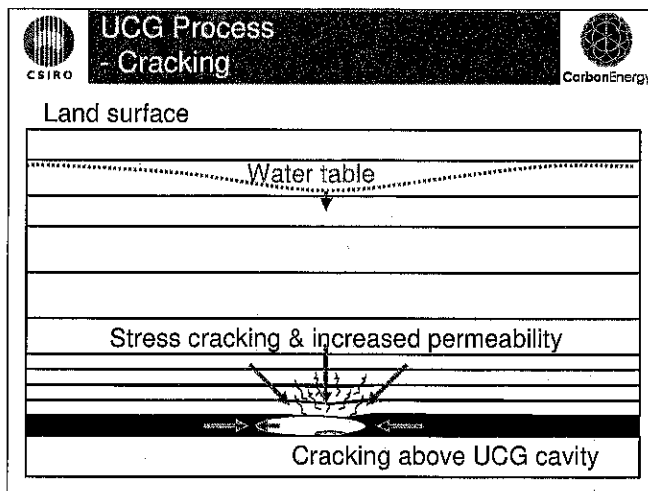
Coal & char reactions  
 Coal/char structural changes  
 Gas flow and reactions  
 Water flows and evaporation  
 Heat transfer  
 Conduction, convection & radiation  
 Rock & coal breakage and collapse  
 Resizing of the matrix with growth



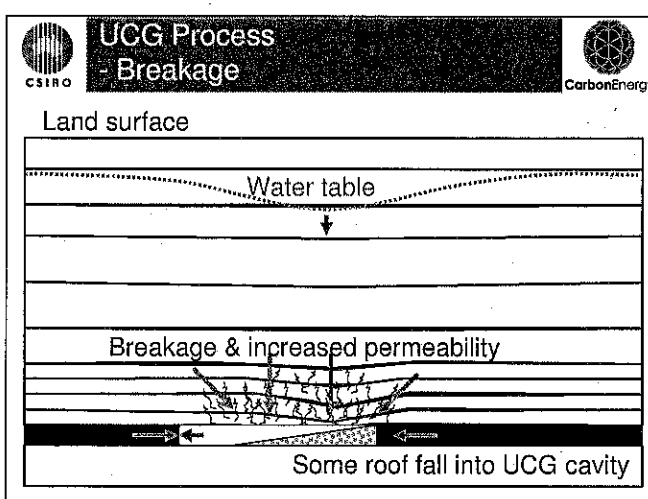
Initiation of gasification in the coal seam.



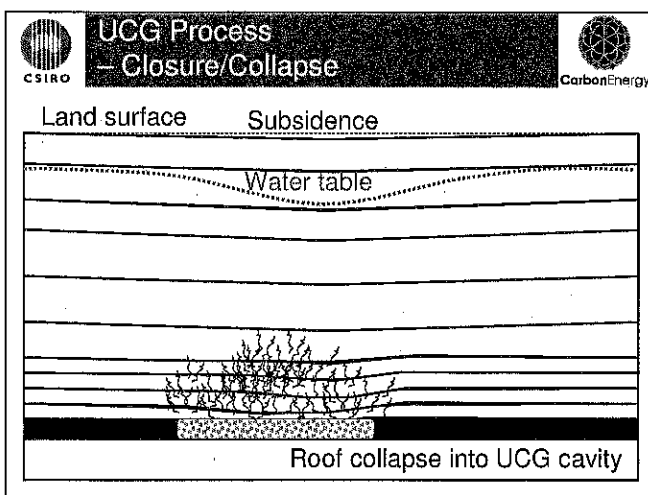
As coal is consumed a cavity grows and water is consumed through drying and reaction, resulting in lowering of the water table. The extent of this will depend on permeability and other geotechnical properties at the site, plus the rate of coal consumption.



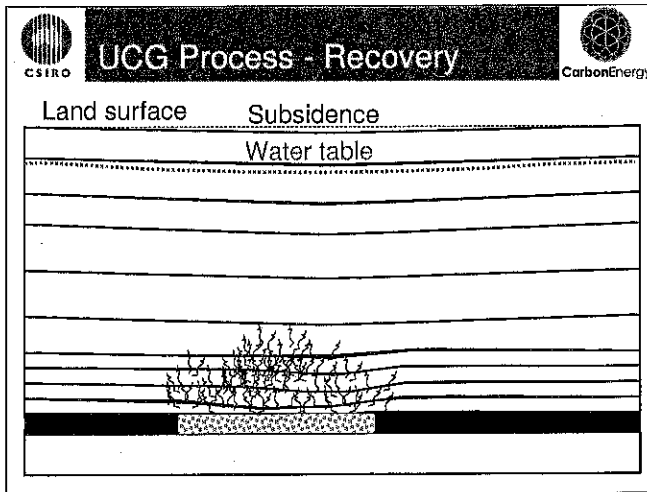
With growth of the cavity there are increasing stresses placed on the overburden. This results in cracking and is likely to increase permeability with a resultant increase in water flow into the cavity.



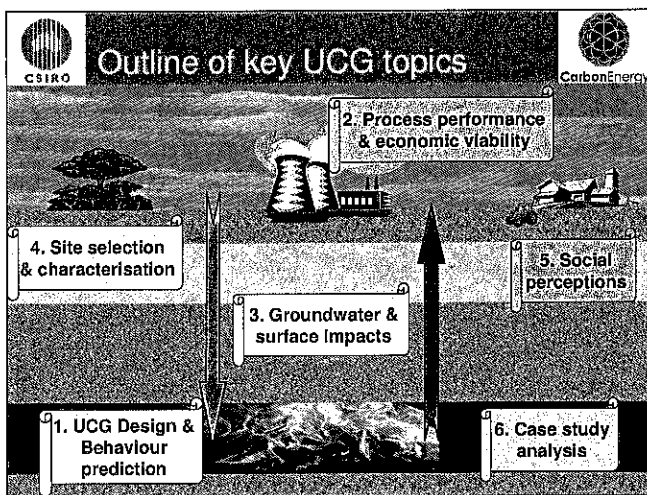
Continued operation will result in some collapse of overburden into the cavity.



After shutdown it is likely that the overburden will slump into the cavity with resultant further cracking of the overburden.



With time the water table will be restored and subsidence will transfer to the surface, with the impact being determined by the site properties and the scale of coal removal. A zone of increased permeability is likely to have been created at the site with possible rearrangement of groundwater flow paths.



A comprehensive approach covering multiple disciplines needs to be used to fully understand the performance of UCG.

## Session 1C: UCG Design

**Session 1C: UCG Design**

Dr Andrew Beath  
CSIRO Exploration & Mining  
Australia

Dr Cliff Mallett  
Carbon Energy Pty Ltd  
Australia

Supported by the Australian Government through the Asia Pacific Partnership (APP) Coal Mining Task Force

Numerous techniques have been used in the over 50 UCG trials that have occurred worldwide. The technique used is influenced by the site characteristics, the availability of different drilling and mining technologies and the desired quality of product gas.



## What affects UCG design?



- ❖ Coal seam dip (slope)
- ❖ Coal seam depth
- ❖ Coal permeability
- ❖ Overburden properties
- ❖ Drilling capabilities
- ❖ Required production volume
- ❖ Restrictions on subsidence and groundwater consumption
- ❖ Process stability requirements



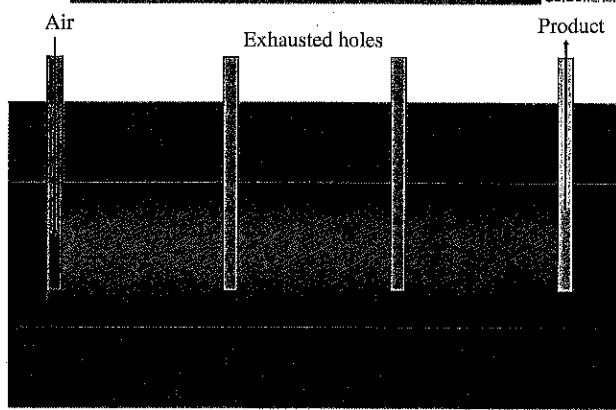
## Historical UCG designs



- ❖ Vertical Wells
- ❖ CRIP (Controlled Retracting Injection Point)
- ❖ SDB (Steeply Dipping Bed)
- ❖ Knife edge CRIP
- ❖ Tunnel

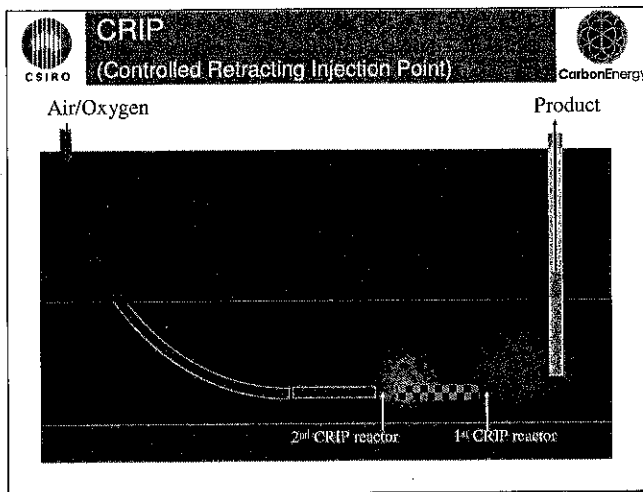


## Vertical wells

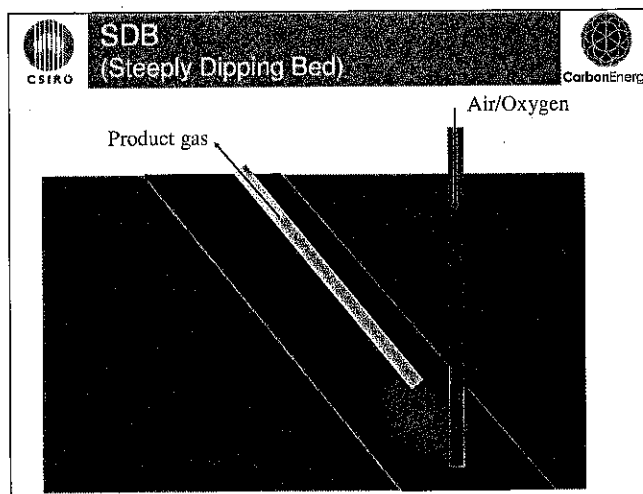


Used in many Soviet operations, early USA trials and the recent Australian trial by Linc Energy

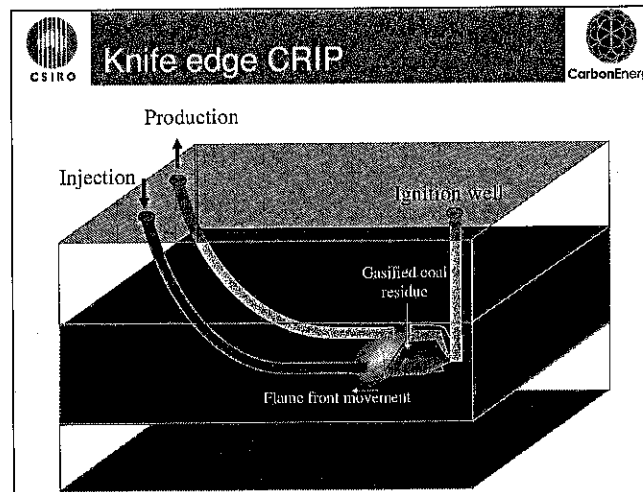
Simple to construct and operate  
Well documented and has been used in large operations (eg. Angren with 5+ million tonnes of coal gasified)  
Becomes expensive when used with deeper coal due to excessive drilling requirements



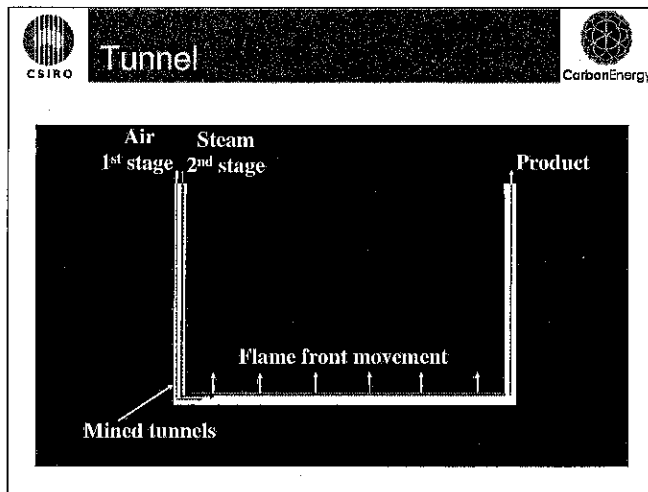
Used in one USA trial and two Western European trials  
 Minimises drilling required, particularly for deeper seams, however uses more expensive directional drilling  
 Accurate knowledge of coal seam location and geometry essential



Used in several Soviet and USA trials  
 Utilises coal seams with dip greater than 50°  
 Various combinations of in-seam and vertical drilling possible  
 Has some control disadvantages due to variations in operating pressure with depth



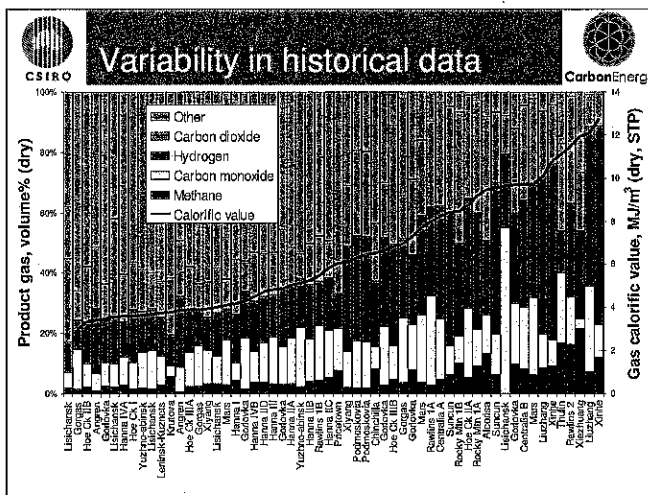
Used in one USA trial  
 Variation of CRIP technique  
 Reaction surface area can be maintained near constant during gasification  
 Less sensitive to faults and other geological defects  
 Multiple wells can be used for a large coal block



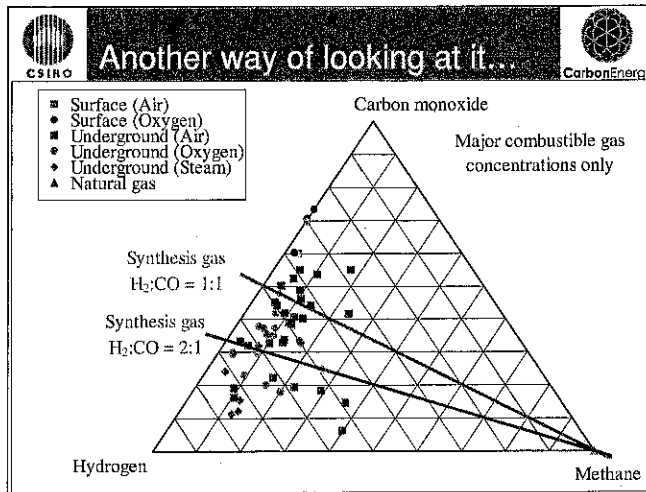
Used in at least 12 trials in China  
 Can be operated in stages  
 First stage uses air to heat reaction area  
 Second stage uses steam to generate a high hydrogen content gas  
 Reactor operates for up to 5 years  
 Requires underground mining

**Behaviour prediction**

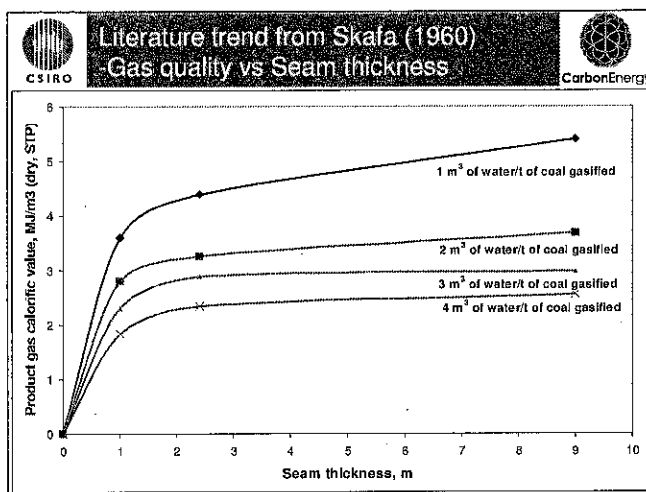
- ❖ There is a large quantity of historical data available, including Soviet era texts detailing performance of UCG in a wide range of coal seams, that can be used to provide indications of likely behaviour
- ❖ Detailed cavity growth and gas production predictions require complex models covering a wide range of scientific disciplines



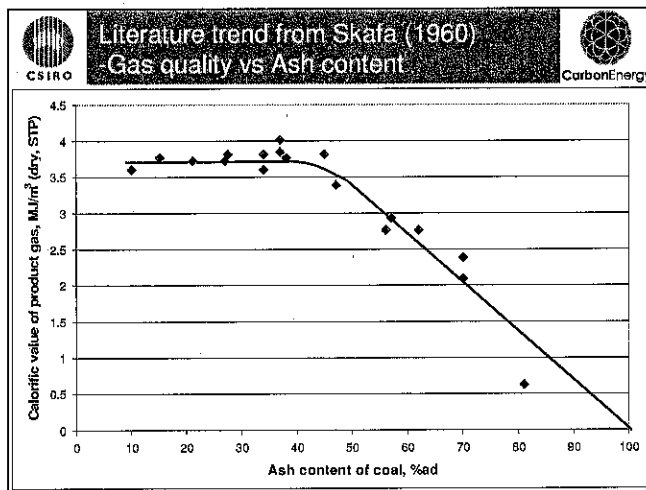
Major variable is the purity of oxygen used, indicated by the nitrogen content (the main component of Other). Methane content has a significant impact on calorific value and is influenced by the depth of operation and operating conditions.



There is a difference in product gas to that from surface gasifiers (eg. Shell & GE). This is mostly due to a lower temperature of gasification affecting the formation of methane.



Water flow has a demonstrated impact on calorific value of the product gas.



Ash content of the coal has a minor impact on product gas quality below 40%, but above this the quality drops. At low contents ash has a stabilising effect on gasification due to the storage of heat in the ash, but at high contents it absorbs too much energy and results in heat dispersion that reduces the operating temperature and efficiency of gasification.





## Summary



Some of the more obvious features that impact on UCG product gas quality are:

- ❖ Seam thickness
- ❖ Water influx
- ❖ Ash content
- ❖ Feed gas composition



## Why do these have impact?



### ❖ Energy balance

- o Heat loss to overburden
- o Vaporisation of water

### ❖ Mass balance

- o Ratio of C:H:O in reactions
- o Coal recovery efficiency




## Ash content impact



Ash content has an unusual impact:

- ❖ Ash replaces carbonaceous material, so reduces the effective quantity of coal and would be expected to reduce the efficiency
- ❖ But, this does not happen until ash contents over 40% occur
- ❖ Ash provides a thermal repository that stabilises gasification and can have a beneficial effect in some circumstances (eg. thin clay or stone bands in the coal seam)

## Session 2A: Behaviour prediction



**Session 2A: Behaviour prediction**

CSIRO CarbonEnergy

Dr Andrew Beath	Dr Cliff Mallett
CSIRO Exploration & Mining	Carbon Energy Pty Ltd
Australia	Australia

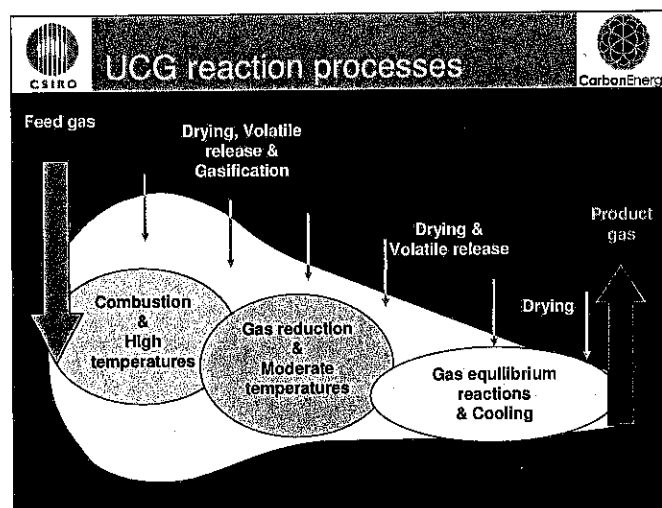
Supported by the Australian Government through the Asia Pacific Partnership (AP6) Coal Mining Task Force

Perhaps the most important requirement for a commercial UCG operation is some method of accurately predicting the behaviour of the operation. This is essential in accurately designing the plant and predicting the financial performance. Without a credible method it will be extremely difficult to instil confidence in the financier of the operation.

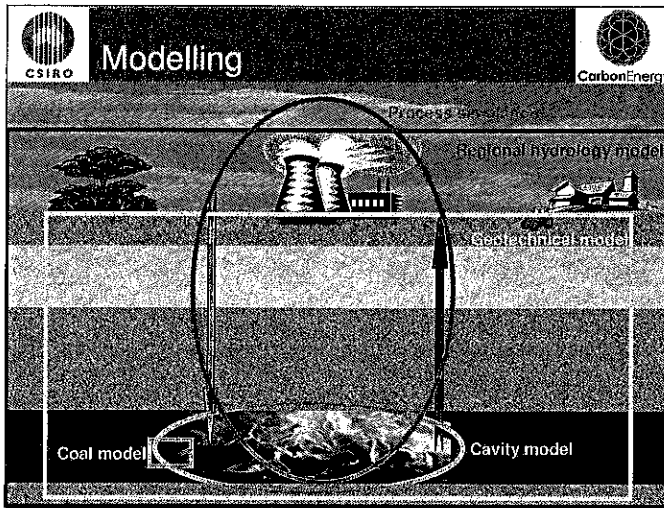
**Behaviour prediction**

One of the key problems with past UCG operations has been the difficulty in understanding what is happening. Many months of data analysis and modelling was required to interpret results from some experimental trials.

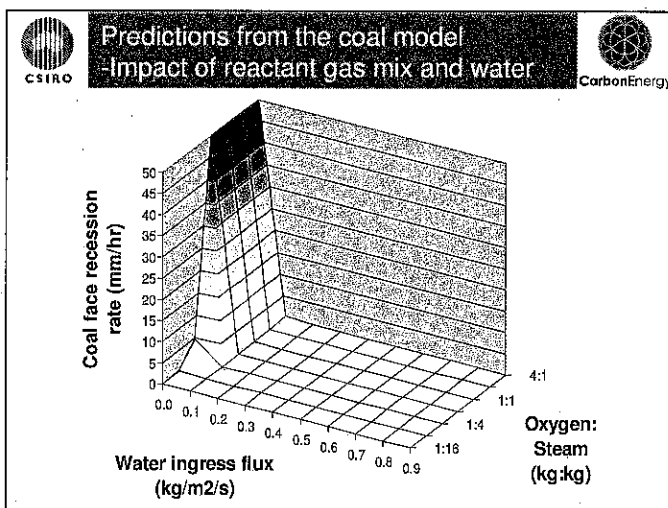
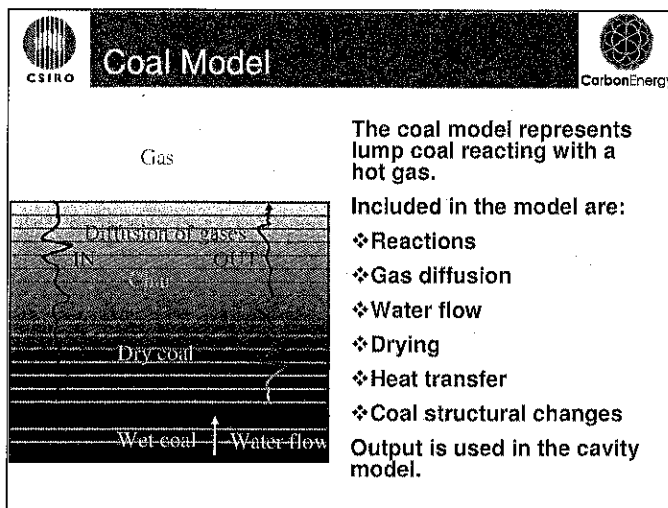
Modern computing allows the opportunity for real-time assessment of the reactor behaviour, if suitable models can be developed.



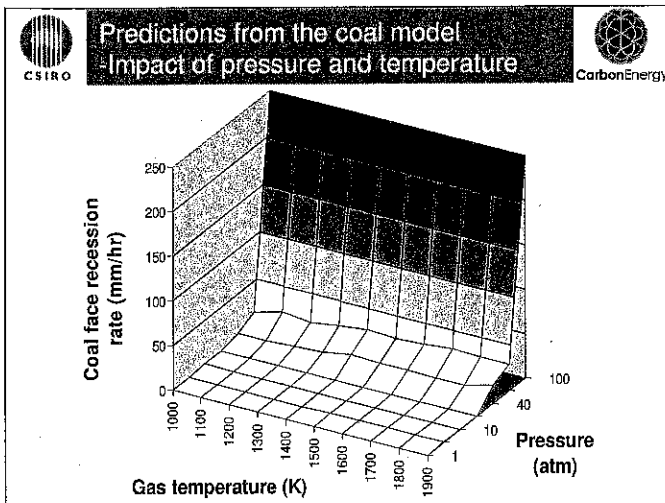
Coal & char reactions  
 Coal/char structural changes  
 Gas flow and reactions  
 Water flows and evaporation  
 Heat transfer  
 Conduction, convection & radiation  
 Rock & coal breakage and collapse  
 Resizing of the matrix with growth



Report also included legislative requirements (related to social perceptions), but there is little applicable legislation if the groundwater is not suitable for human consumption.



Water and low oxygen levels reduce the operating temperature and slow reaction.



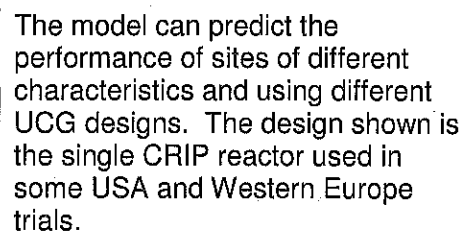
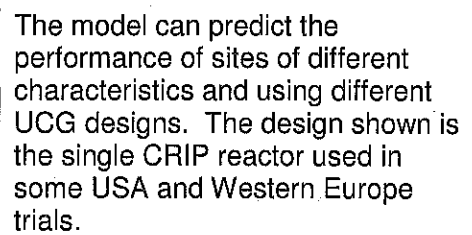
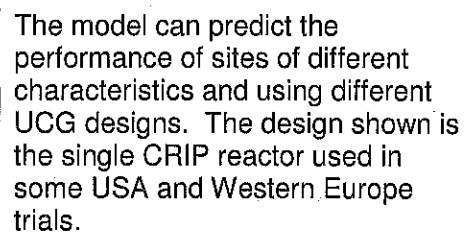
The reaction temperature of the coal is only marginally affected by gas temperatures, but pressure has a major impact.

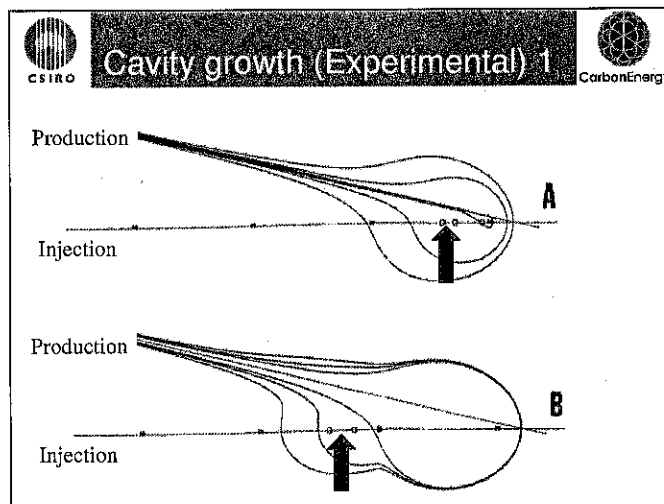
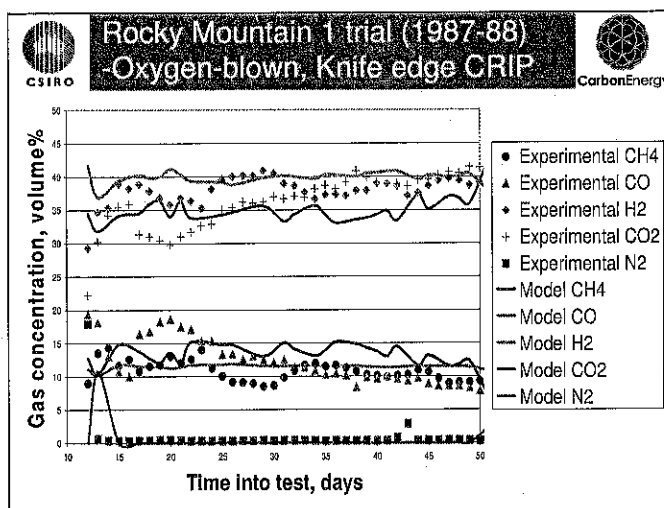
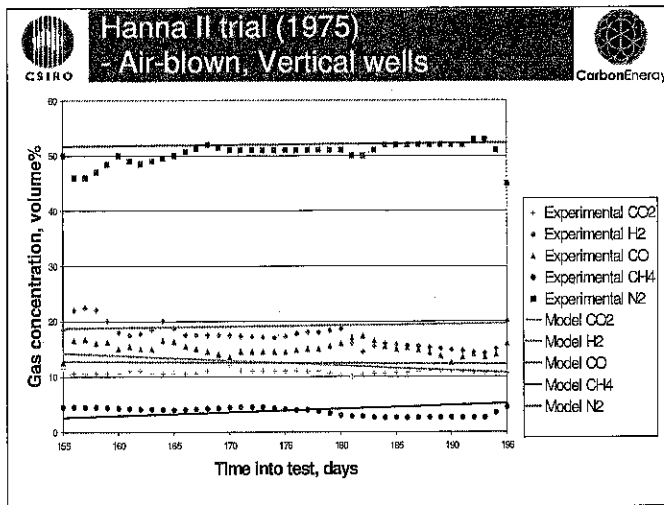
**Use of the coal model**

- ❖ Does not provide standalone predictions relevant to UCG as it neglects many of the gas flow and heat transfer features of real cavities
- ❖ Makes spot predictions of coal behaviour under pseudo-steady state conditions to feed into more complex models
- ❖ Can be used to predict the general operating regimes that are desirable for efficient gasification

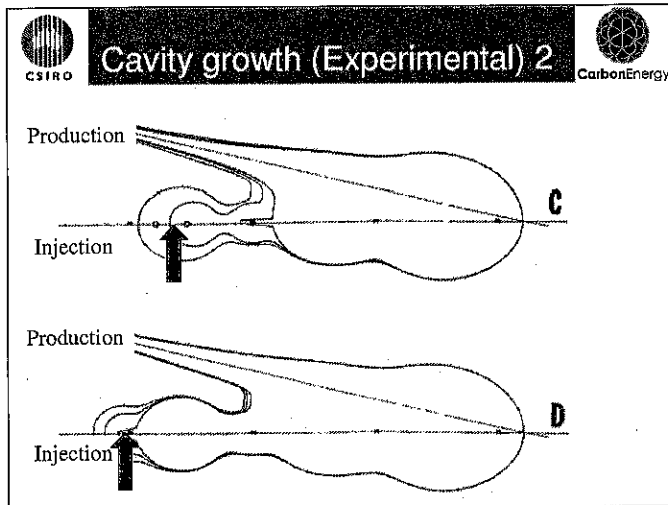
**Elements of a cavity model**

- ❖ Coal & char reactions
- ❖ Coal/char structural changes
- ❖ Gas flow and reactions
- ❖ Water flows and evaporation
- ❖ Heat transfer
  - Conduction,
  - Convection
  - Radiation
- ❖ Rock & coal breakage and collapse
- ❖ Resizing of the matrix with growth





The RM1 site had a complex shape of gasifier due to the gasification layout and a minor fault through the seam. This resulted in a very unusual gasifier shape that is very hard to predict. The injection pipework also melted in a semi-controlled manner, so the injection point moved during operation without the CRIP procedure.



**Model performance**

**Predicts accurately:**

- o Cavity volume changes
- o Product gas composition and flow

**Hindrances to model performance:**


- o Requires detailed site information
- o Experimentally, the cavity shape was affected by uncontrolled shortening of the 'CRIP' and an undetected fault running through the site

**Physical site changes**



**Modelling of other side of UCG, the physical site changes, will be discussed in a later session.**

**In the cavity modelling, simplified models are used for roof collapse and hydrological flows and these are 'tuned' using output from the more complex and specialised geotechnical and hydrological models.**

## Session 2B: Process performance and economic viability





**Session 2B: Process performance & economic viability**



<b>Dr Andrew Beath</b> CSIRO Exploration & Mining Australia	<b>Dr Cliff Mallett</b> Carbon Energy Pty Ltd Australia
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As a follow-on to behaviour prediction, the output from the UCG component of the process must be incorporated into prediction of the UCG product utilisation process, as it is this that will produce a saleable product.

 **Historical utilisation of UCG gas** 

- ❖ Most Soviet-era UCG produced a fuel gas for use as supplementary fuel in coal-fired boilers, so gas specification was not stringent
- ❖ Chinese UCG is commonly used for domestic fuel gas, but has been used for hydrogen production and as a synthesis gas for ammonia production
- ❖ Rawlins II trial in the USA demonstrated reliable synthesis gas production and a subsequent (failed) commercial plant at the site was intended to synthesis methane

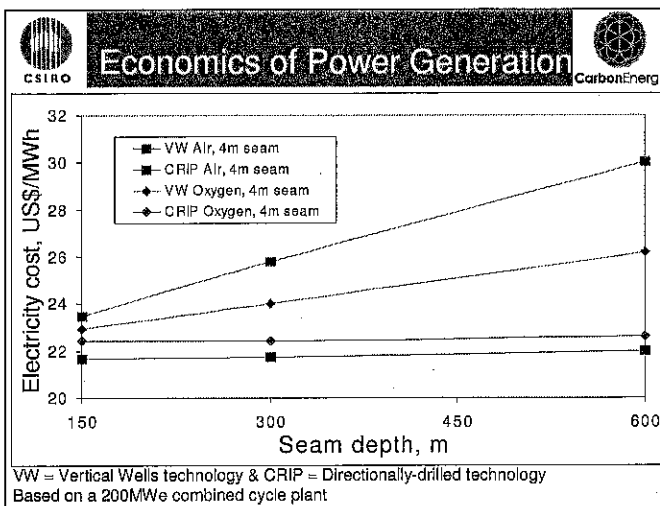
 **Modern applications for the UCG** 

- ❖ The product gas can be used as a:
  - o FUEL
    - Electricity production via gas turbines
  - o SYNTHESIS FEEDSTOCK
    - Production of chemicals (eg. fertilisers)
    - Synthesis of liquid fuels (Fischer-Tropsch)





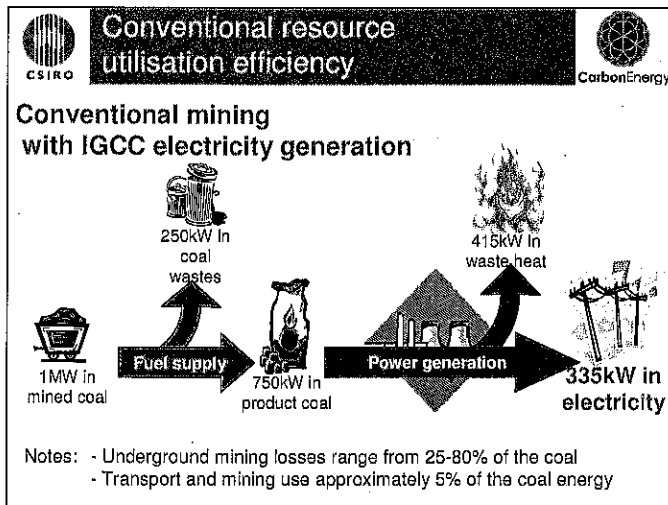
Process efficiencies for combined cycle electricity generation	
Process	Efficiency
Air-blown UCG	45.4 %
Oxygen-blown UCG	46.5 %
UCG with CO <sub>2</sub> separation	39.8 %
Conventional coal	~37 %
IGCC	~45 %



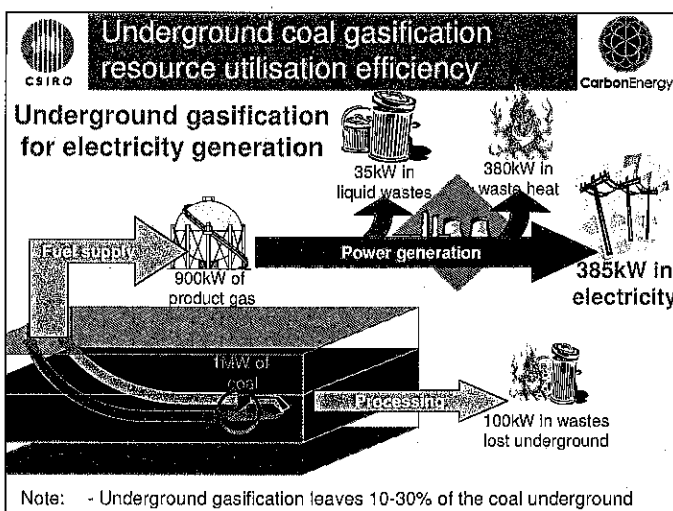
This is illustrative of the impacts of coal seam depth and UCG technology on economics. Typically, air-blown UCG with vertical wells is applicable to shallow coal seams while oxygen-blown CRIP technology is for deeper coal seams.

**Resource utilisation efficiency**

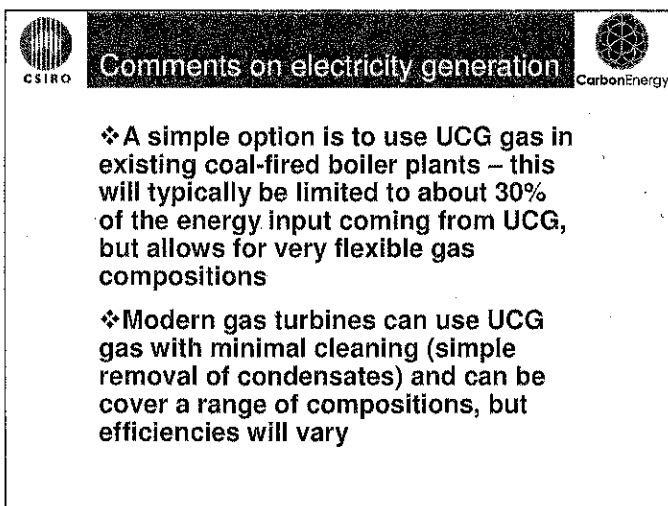
An alternative viewpoint is in terms of resource utilisation efficiency, so how does UCG compare with conventional mining and IGCC in resource utilisation efficiency?




The conventional approach with mining and surface gasification requires a relatively low ash coal supply, so there are significant losses in coal preparation before utilisation. Often there is also significant wastage of coal in the mining process due to partial extraction.




UCG has the benefit of being suitable for even relatively high ash coals, while maintaining similar efficiencies in the utilisation process so there is a more efficient overall efficiency in coal utilisation.





CSIRO

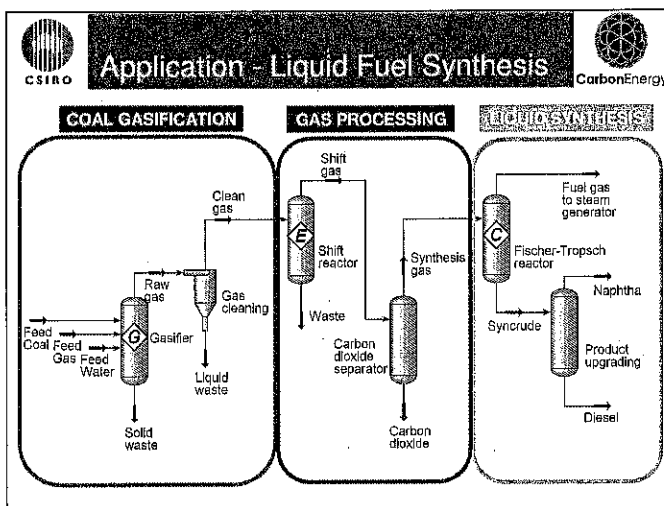
## Liquid fuel synthesis



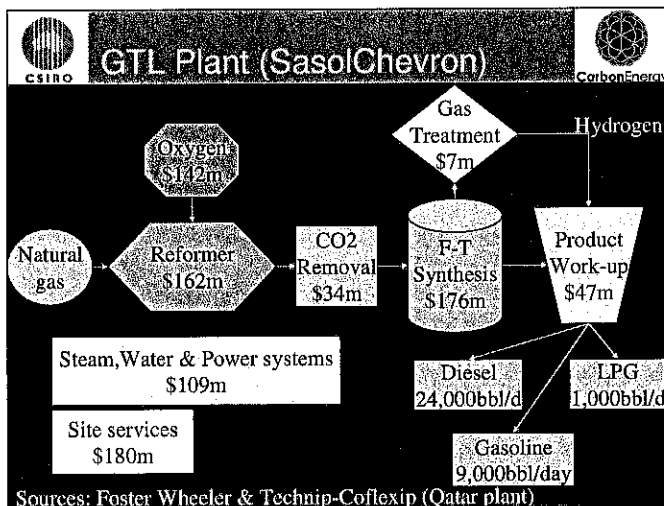
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❖ UCG is a low cost option for providing gas for Fischer-Tropsch synthesis of liquid fuels

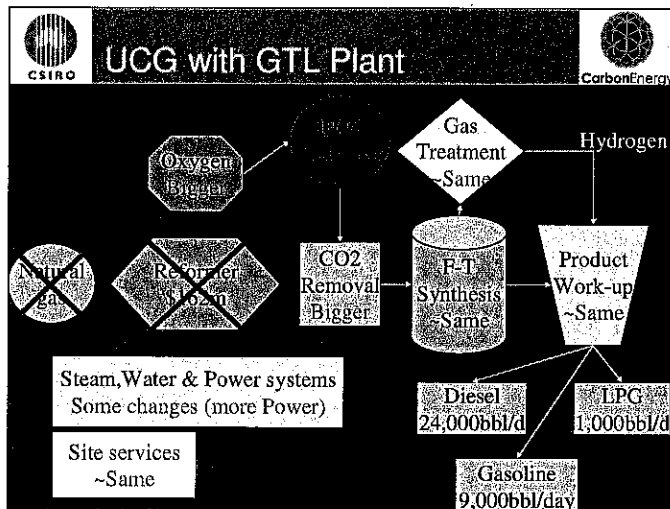
❖ This is a tempting process to consider due to the high value of the products, but the capital cost of the synthesis plant is very high



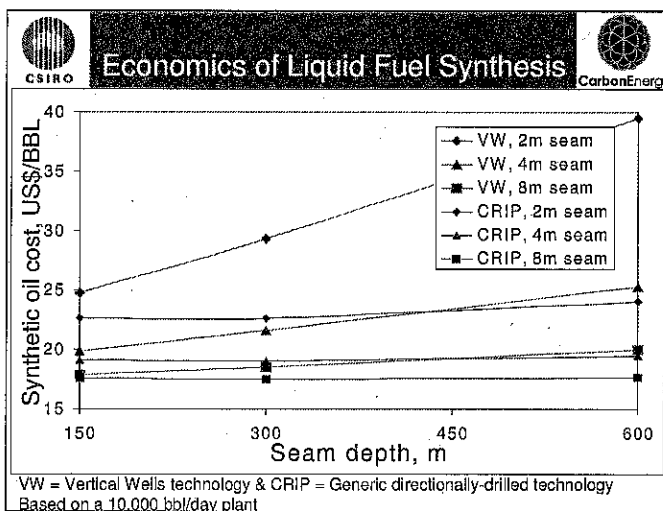
Simplified process diagram for a straightforward plant producing mostly diesel and naphtha (petrol/gasoline). More complex configurations can extract high value products, such as waxes, but have higher capital cost.



This is based on published data for a plant in Qatar that uses a stranded natural gas feed.



Some modification of the process is required to convert the process to using UCG gas as feed. Some changes increase cost and some reduce cost. The analysis needs to be performed in a detailed manner in consultation with plant suppliers for an accurate analysis and the analysis presented here is relatively simple with several basic assumptions.




A simplified economic analysis. There can be significant byproducts of electricity and other hydrocarbons that complicate analysis of the plants. This also shows the impact of seam thickness, depth and technology on the economics.


**Comments on liquid synthesis**

- ❖ The gas specification for this process is much more stringent than for electricity generation and it will be difficult to convince financiers that UCG alone can supply a reliable gas feed
- ❖ Large scale UCG with gas blending can maintain constant composition, but may lead to environmental problems

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Comments




Process simulation is necessary for prospective plants using UCG as:

- ❖ Often the plant will have a tight integration between surface and underground operations
- ❖ Differences between the UCG gas and conventional gases may have a significant impact on the surface plant operation

### Session 3A: Groundwater & surface impacts



Session 3A: Groundwater & surface impacts




**Dr Andrew Beath**  
CSIRO Exploration & Mining  
Australia


**Dr Cliff Mallett**  
Carbon Energy Pty Ltd  
Australia

Supported by the Australian Government through the Asia Pacific Partnership (AP6) Coal Mining Task Force

Environmental impacts are important factors in the commercialisation of new technologies. Some of the historical UCG operations have had mixed environmental outcomes, making a detailed analysis essential if approvals are to be obtained for operation to commence.



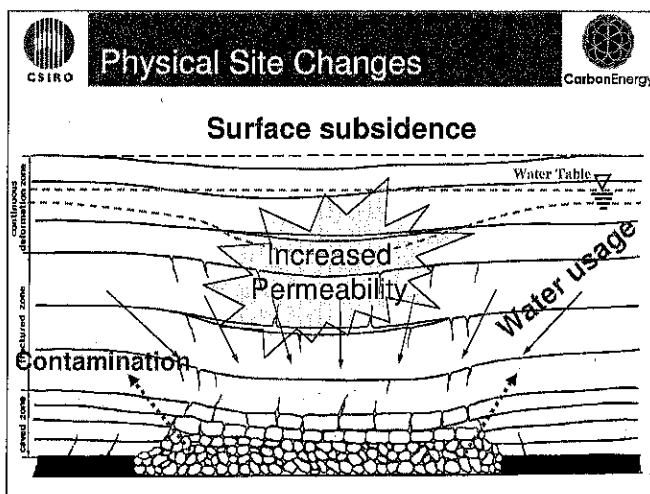
Potential environmental concerns



**Depending on the site and its geological characteristics, the major potential problems from UCG are:**

- o Subsidence
- o Groundwater depletion
- o Groundwater contamination

**Other environmental issues, like waste water handling, can be handled using conventional equipment from existing industries**



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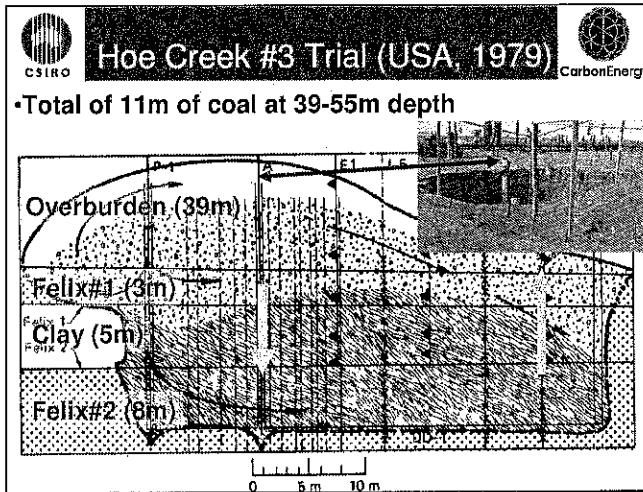
### Subsidence

- ❖ UCG, like any other coal extraction technique, will cause some subsidence
- ❖ The *magnitude* of this will be determined by the seam thickness, depth, site geotechnical properties and the UCG design
- ❖ The *impact* will depend on surface land use

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### Subsidence - Historical

- ❖ Much of the Soviet and American experimentation took place in shallow, thick coal seams
- ❖ This minimises the cost of operation, but maximises the likely magnitude of subsidence

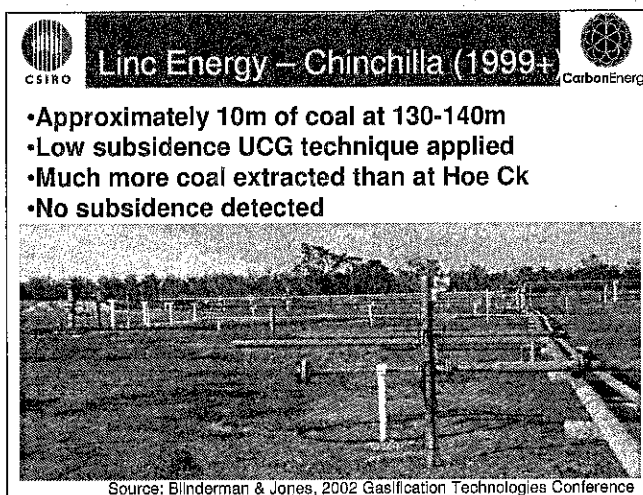


This shows the cavity generated during the Hoe Ck #3 trial, which had both subsidence and groundwater contamination issues.

The objective was to gasify a section of the Felix#2 coal seam using single injection and production wells (indicated with arrows).

In reality, the overlying Felix#1 seam was also gasified with the resulting growth of a large cavity.

Given the shallow depth, the resultant subsidence opened to the surface.



**Notes on Subsidence**

- ❖ Subsidence can be an issue, but can be minimised through careful site selection and UCG design
- ❖ Besides environmental impact, it will also have substantial process control ramifications if at excessive levels, so must be addressed during planning





## Groundwater Depletion

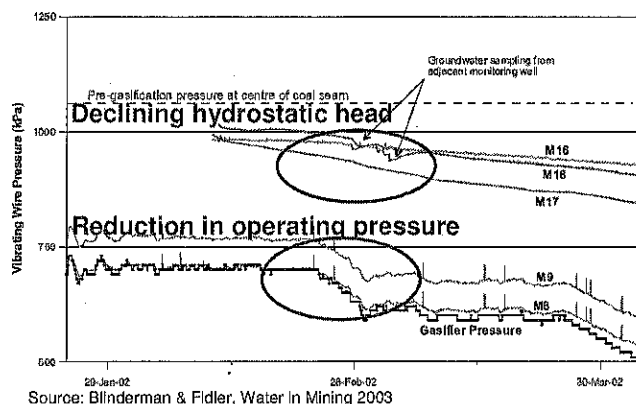


### ❖ Impacts:

- o Shortages for other users of groundwater (eg. agricultural)
- o Can lead to high gas losses from the UCG operation (→ Contamination)
- o Product gas composition changes and production pressure declines, with possible impact on the gas utilisation process



## Linc Energy – Chinchilla (1999+)



This shows that decreasing hydrostatic head impacts on the process operating pressure. Depending on the process that is using the product, this change in operating pressure could result in significant decline in process performance. Deeper sites are less likely to have significant changes compared to shallow sites.



## Notes on Groundwater Depletion



- ❖ Depletion is site dependent but should be less than for other resource utilisation methods (eg. Coal Bed Methane or Underground Mining) when performed on a similar scale
- ❖ Plant size will have a large impact and this may be a limiting factor in specifying the plant design



## Groundwater Contamination



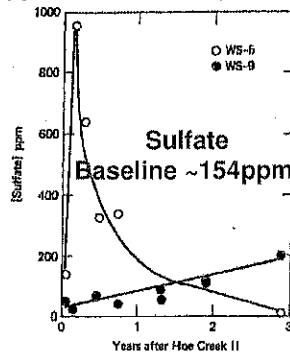
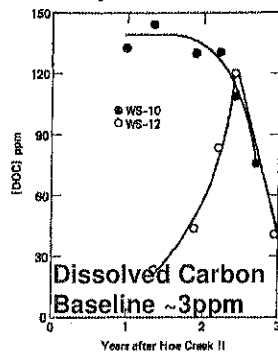
- ❖ Benzene and other organics have been found in groundwater near two UCG sites in the USA
- ❖ Organic contamination is linked to high operating pressures and was avoided in subsequent US trials
- ❖ Soviet testing identified elevated salt concentrations around a large UCG site after closure, but these rapidly decreased to background levels



### Hoe Creek II (USA, 1977)



- Hoe Creek II ran at a 300kPa operating pressure
- The hydrostatic head dropped to essentially zero




The operating pressure at Hoe Creek II exceeded the hydrostatic pressure significantly which resulted in contaminants being spread outside the cavity zone.




### Hoe Creek site (USA, 1973-2003)



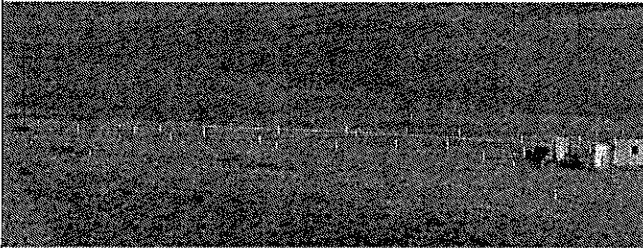
- ❖ Contamination was noted in 1977, but did not exceed the limits for livestock watering
- ❖ The US government committed to cleaning up old DOE sites in 1991
- ❖ Clean-up started in 1995 and continued intermittently to 2003
- ❖ Contaminant limits were set by Wyoming State as "Not Detectable" due to the lack of a site environmental licence and full background testing prior to the trials




### Hoe Creek site (USA, 1973-2003)




- Initially, the groundwater was extracted and filtered through activated carbon
- Then combined air-sparging and bio-remediation was performed
- Later, only air-sparging was used



Hoe Creek II, October 2002




### Summary




- ❖Environmental issues are largely determined by the combination of site characteristics, gasifier design and the operating conditions.
- ❖Analysis of these for a prospective UCG process will be the major focus of the case study analysis

## Session 3B: Site selection & characterisation



### Session 3B: Site selection & characterisation



Dr Andrew Beath  
CSIRO Exploration & Mining  
Australia

Dr Cliff Mallett  
Carbon Energy Pty Ltd  
Australia

Supported by the Australian Government through the Asia Pacific Partnership (APP) Coal Mining Task Force

Given the site specific nature of UCG, it is important that site selection criteria be established to assist in identifying suitable sites, then detailed characterisation of the sites is essential if predictions of site performance are to be valid.



## Site selection criteria



- ❖ It is possible to set a series of guidelines that simplify decision making when selecting UCG sites
- ❖ Several proposed sets of criteria from the UK, USA and Australia are given on the following slides, however, all are based heavily on Soviet experience with bias towards local conditions



### UK site criteria 1 (National Coal Board, 1976)



- ❖ 5 Mt of coal in resource to provide 20 years of operation
- ❖ Not marked for conventional mining
- ❖ Not adjacent to working mines
- ❖ Removal won't cause unacceptable subsidence
- ❖ Seam thickness at least one metre, or banded seam totals over one metre
- ❖ Depth greater than 20 metres to minimise gas leakage



### UK site criteria 2 (National Coal Board, 1976)



- ❖ Ash content less than 60%, including any dirt bands, as combustion may be impeded
  - ❖ Area free of excessive faulting
- Other notes:
- ❖ Leakage may be excessive if adjacent to old mine workings or in faulted area
  - ❖ Impact of faulting and roof material on operation largely unknown
  - ❖ Progress and control of multi-seam operations poorly defined
  - ❖ Expect initial operations at 3 times the manpower efficiency of conventional mining (rising to 10 times)



### US site criteria 1 (Williams, 1982)



- ❖ Seam thickness greater than 1 m or 0.6 m for steeply dipping seams
- ❖ Avoid variable thickness seams
- ❖ Avoid seams with multiple partings
- ❖ Avoid seams with overlying coal within 15 m that is thicker than 0.6 m
- ❖ Minimum of 3.5 Mt
- ❖ Minimum overburden of 100 m
- ❖ Minimum of 1.6 km from populated (>100 people) areas
- ❖ Minimum distance of 0.8 km from major faults
- ❖ Minimum distance to oil/gas recovery development of 1.6 km



### US site criteria 2 (Williams, 1982)



- ❖ Minimum distance of 0.4 km from major highways and rail
- ❖ Minimum distance of 1.6 km from rivers and lakes
- ❖ Minimum distance of 3.2 km from active mines
- ❖ Minimum distance of 1.6 km from abandoned mines

#### Other notes:

- ❖ Steeply dipping (>30°) seams favoured due to lack of mining interest
- ❖ Floor and roof conditions "examined"



### CSIRO site criteria 1



- ❖ Seam thickness >5 m
- ❖ Coal ash <40% (air dried basis)
- ❖ Seam dip <20°
- ❖ Seam depth 200-400 m
- ❖ Minimal faulting and no dips/sills
- ❖ Roof thermally stable with minimal permeability, preferably structured to encourage even caving



## CSIRO site criteria 2



- ❖ Hydraulic head >200 m
- ❖ Adjacent aquifers contain poor quality water and are of minimal permeability
- Other notes:
- ❖ Limited human activities in vicinity
- ❖ No waterways overlying the site
- ❖ Subsidence must be acceptable at location
- ❖ Coal resource size suitable for long term operation



## Site selection summary




- All sets of criteria are based around:
- ❖ Establishing that it is an economic resource of suitable size
  - ❖ Geological conditions are suitable for consistent coal removal
  - ❖ Environmental impacts are acceptable
- A comprehensive analysis will still have to be performed to ensure that the site is suitable, but use of simple criteria can eliminate unsuitable sites quickly



## Site characterisation




- ❖ Accurate characterisation of a site will take a similar amount of exploration work to development of an underground coal mine
- ❖ Failure to do this has resulted in serious errors in a number of past trials



CSIRO


## Important characteristics



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- ❖ Coal seam definition  
(continuity, partings, interburden, etc)
- ❖ Coal properties  
(ash, permeability, etc)
- ❖ Overburden properties  
(permeability, strength, thermal behaviour, etc)
- ❖ Aquifer properties  
(locations, permeability, water quality, etc)

### Session 3C: Social perceptions



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## Session 1C: Social perceptions



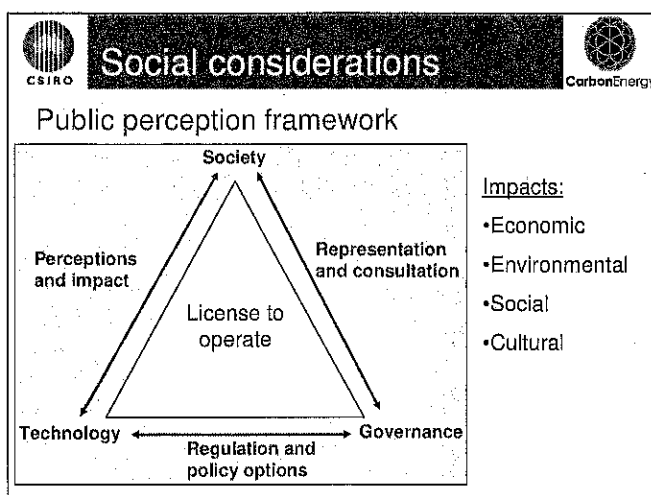
CarbonEnergy



Dr Andrew Beath  
CSIRO Exploration & Mining  
Australia

Dr Cliff Mallett  
Carbon Energy Pty Ltd  
Australia


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Any new technology is subject to scrutiny by various parts of society, be they government legislators, environmental lobby groups or the general community. It is becoming more important to ensure that information on a proposed development be communicated carefully to ensure society accepts the value of the development. By examining the existing perceptions of the technology in society it may be possible to address misconceptions to ease the development process.





 <b>Public perception survey</b> 	
Benefits of UCG	Prospective concerns with UCG
<ul style="list-style-type: none"> <li>❖ Better way of exploiting coal reserves</li> <li>❖ Economic benefits</li> <li>❖ Economic benefits to regional economy</li> <li>❖ Environmentally beneficial</li> <li>❖ Benefits to regional community</li> </ul>	<ul style="list-style-type: none"> <li>❖ How safe is it?</li> <li>❖ Who's monitoring / controlling things overall?</li> <li>❖ What impact will it have on people's property?</li> <li>❖ What about the impact on the environment?</li> <li>❖ Is it economically beneficial to the region?</li> <li>❖ Will we be kept properly informed?</li> <li>❖ Aren't there better ways of investing in emerging energy sources?</li> <li>❖ Who's really going to benefit from this, and when?</li> <li>❖ Don't believe that politicians, scientists or business will be truthful with us</li> </ul>

In the regional part of the survey there is a general view that the resource will be exploited without benefiting the region significantly. In the city part of the survey there was more concern for broader environmental issues.




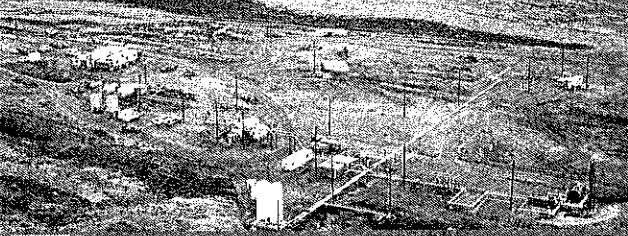

Then there is the media...





New Scientist (1 June 2002) article on underground coal gasification. This is one of four pictures in the article showing coal fires caused by conventional coal mining activities in India (we think). There are no known outbreaks of this type relating to UCG activities, which are typically deeper and operate under the water table.

#### Session 4: Case study analysis


**Session 4A: Case study analysis**

<p>Dr Andrew Beath CSIRO Exploration &amp; Mining Australia</p>	<p>Dr Cliff Mallett Carbon Energy Pty Ltd Australia</p>
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Supported by the Australian Government through the Asia Pacific Partnership (AP6) Coal Mining Task Force

A detailed analysis of a prospective UCG site has been prepared to demonstrate the modelling tools that are available and examine the likely environmental and financial performance of the site.

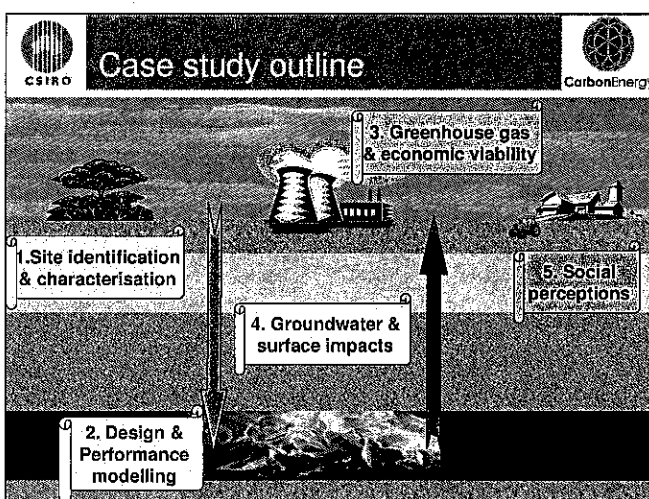





## Case study analysis




- ❖ A case study showing the procedures used to develop a process utilising UCG
- ❖ The target development is a nominally 400MWe electricity generation plant with the option to separate carbon dioxide for Greenhouse emission reduction



Report also included legislative requirements (related to social perceptions), but there is little applicable legislation if the groundwater is not suitable for human consumption.

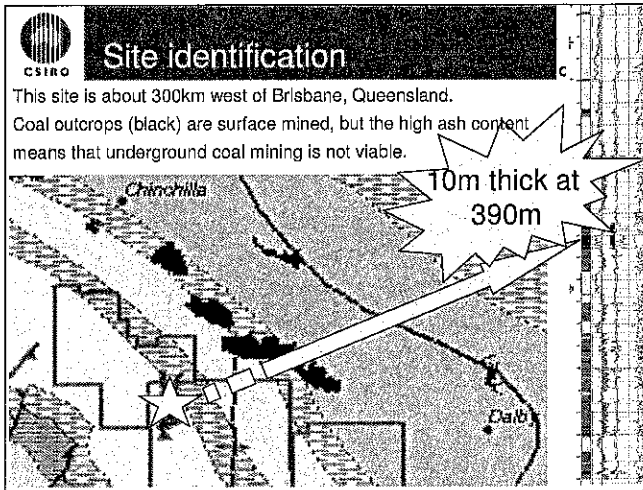


## Site identification & characterisation

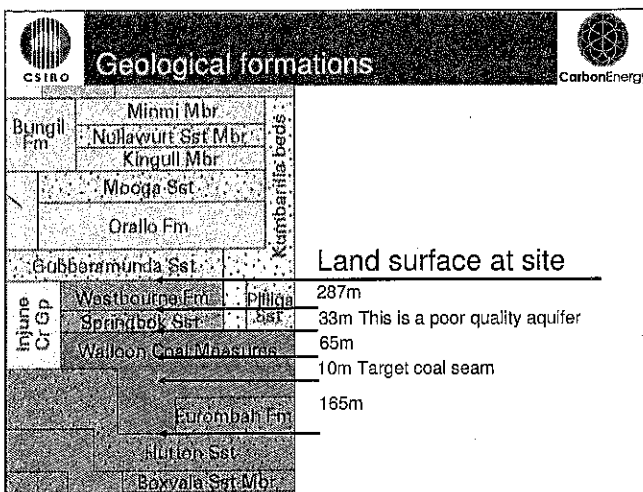


- ❖ Objective: A site with deep & thick coal that is not near good water aquifers and is relatively free of geological discontinuities
- ❖ The Eastern Surat Basin (Queensland, Australia) was selected for further study and a 3D regional geological model was prepared to assist in identifying a suitable site

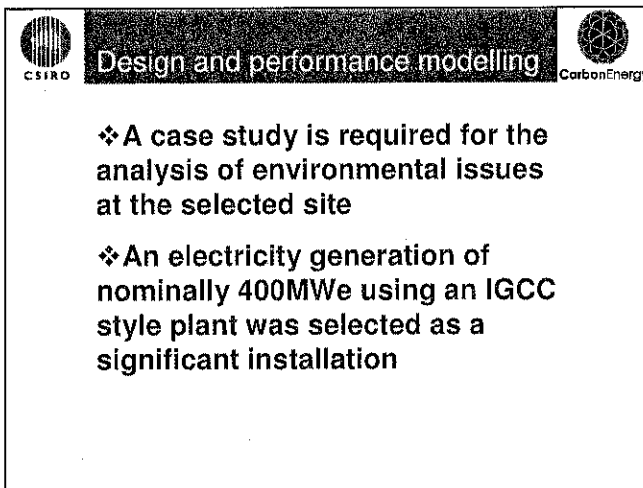
The geological model combines data from thousands of bores and cores in the region at provides a predictive tool for the extent and characteristics of different geological strata. It can be used to generate geotechnical and hydrogeological data (for example permeabilities) for use in other models.

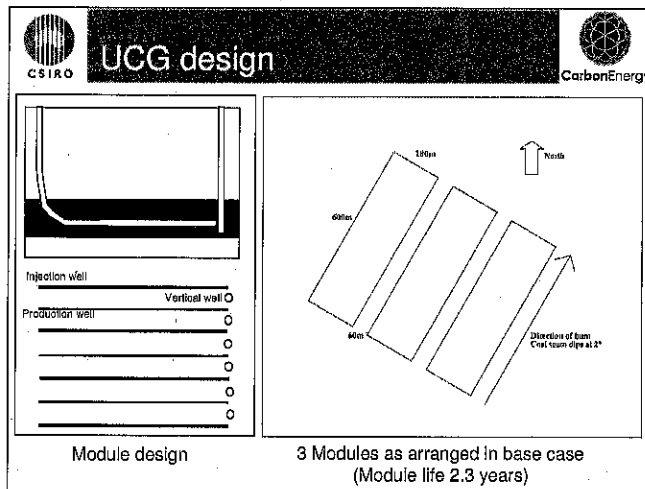


Different colour bands show approximate locations of outcropping for different strata and the black blobs are identified deposits of coal at less than 100m depth. These should be also present at greater depth. The core log to the right shows the different strata at the site with the coal of interest being a band of several seams totalling ~10m thickness at 390m depth. This appears to be the same band as is mined at nearby Wilkie Creek where it outcrops.

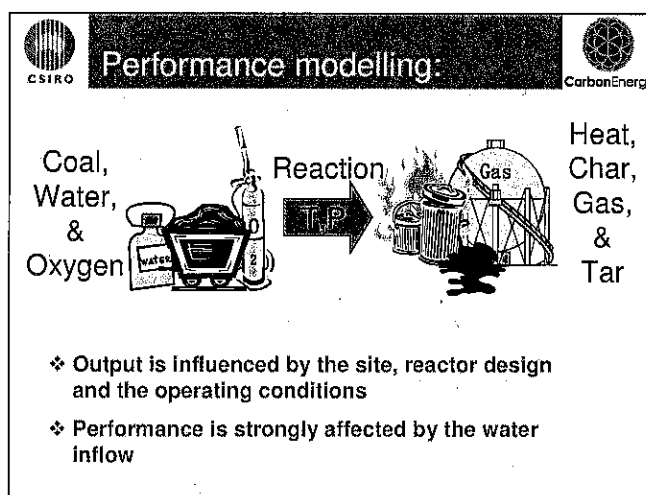


This shows the generic strata of the Surat region. At the site of interest the upper aquifer systems that constitute the Great Artesian Basin are NOT present. The target coal seam is in the Walloon Coal Measures and is a poor water quality aquifer, as is the overlying Springbok aquifer.

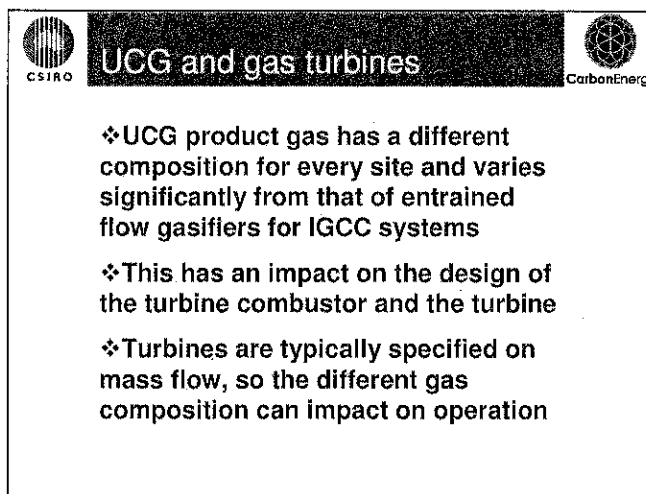


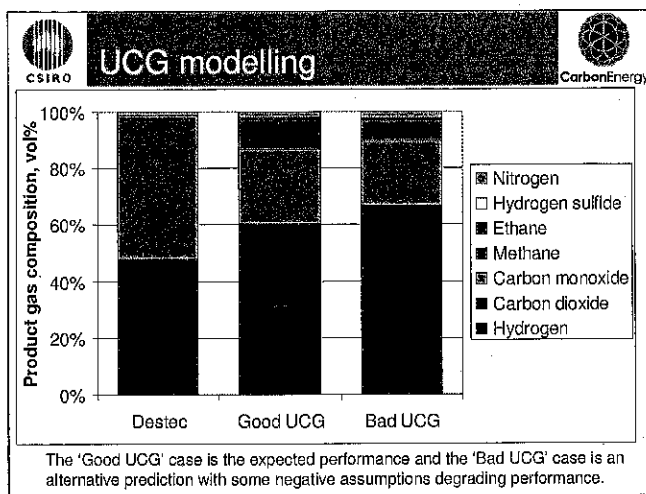


The module design uses parallel directionally drilled wells for injection and production duty, plus vertical wells for ignition and water control. A coal module contains approximately 1.4million tonnes of coal. The base case was defined as 3 adjacent modules operating simultaneously, which would provide sufficient gas for a nominal 400MWe power plant based on a IGCC cycle.



An assumption as to water consumption must be made initially and feedback from the hydrology modelling will correct this. In the base case the assumed water inflow was high and some increase in performance could be expected in subsequent refinement of the modelling.



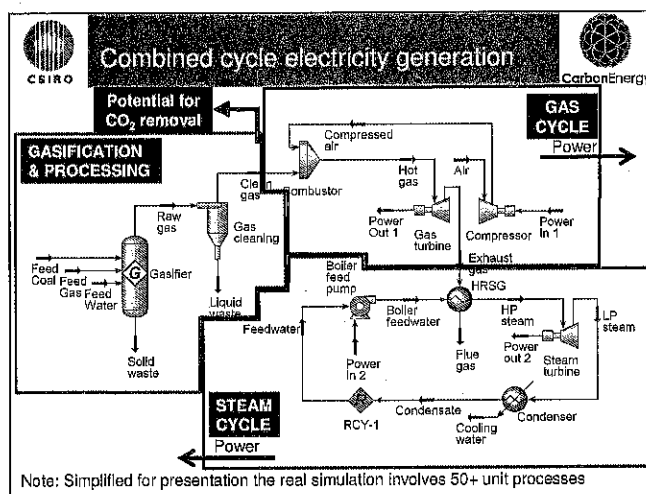


The Destec figures are from a study of an IGCC system with an entrained flow gasifier.

Good UCG is a conservative base case, while Bad UCG has exaggerated heat loss and water inflow.

The higher CO<sub>2</sub> of the UCG gases is misleading – the UCG cases have C:H of about 0.62 versus 0.75 for the Destec case, arising from char left in the ground and tar that is removed from the gas.

Significant differences in the processes are in the consumption of oxygen and the density of the product gas.



This is a standard IGCC type process using UCG product gas.

Modifications to this process to incorporate carbon removal for sequestration have been considered.

We have also looked at the process rearrangements required to utilise the product gas in Gas To Liquids processes to produce synthetic liquid fuels

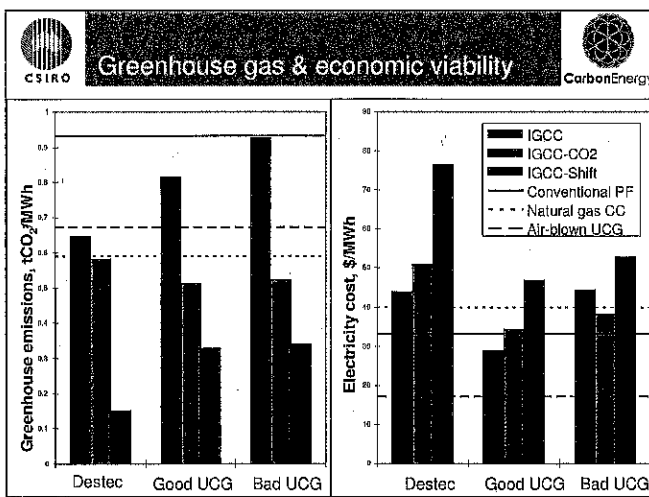
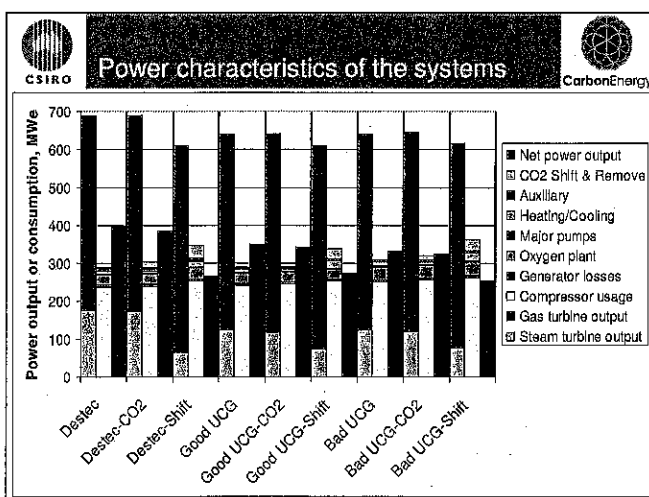
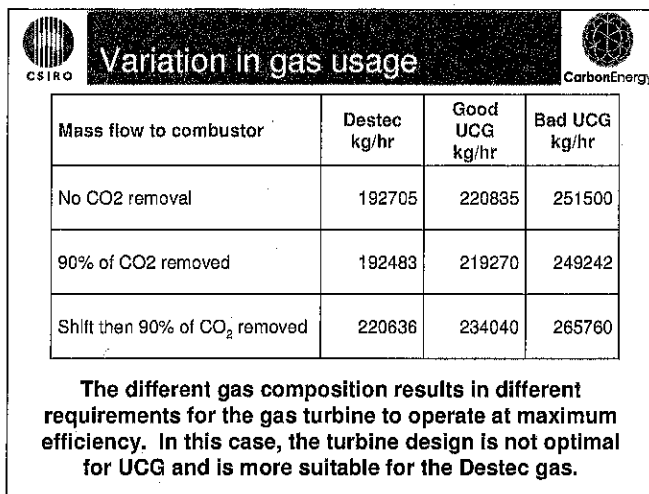
**Process options**

Process	Feed gas
Gas turbine combined cycle (IGCC)	Surface coal gasifier (Destec)
IGCC with CO <sub>2</sub> removal (IGCC-CO <sub>2</sub> )	UCG base case (Good UCG)
IGCC with Shift and Removal (IGCC-Shift)	UCG "worst" case estimate (Bad UCG)

Note: All processes use commercially available technologies

Total of NINE cases simulated and costed.

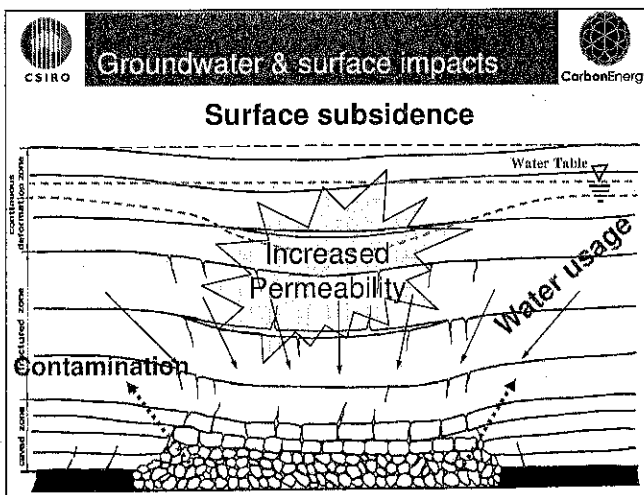
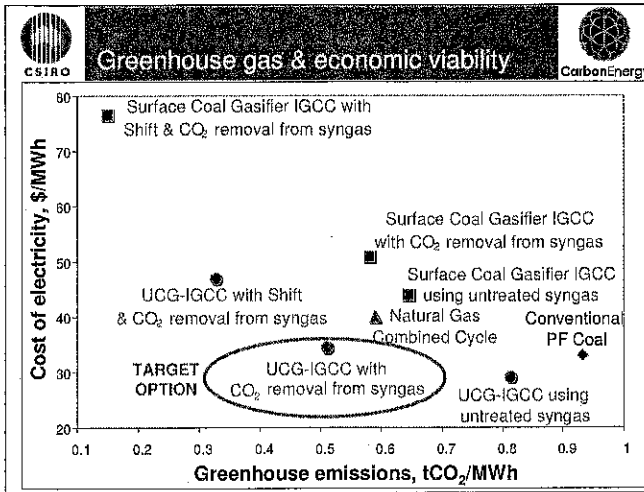
Processes simulated using a combination of HYSYS.Process in-built modules and CSIRO models for specialised components (eg. UCG, CO<sub>2</sub> removal and Shift reactors). Costing based on NETL (2001) publications and CSIRO costing, with electricity cost using EPRI levelised costing.



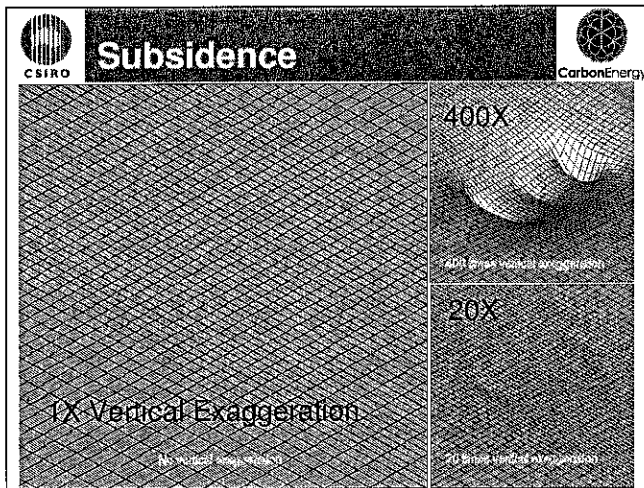
The three different processes are shown as different colours, the different feed gases are on the X axis. Lines are from CISS and other CSIRO studies. The air-blown UCG numbers are based on the Linc Energy trial at Chinchilla and are better than the oxygen-blown if CO<sub>2</sub> removal is not considered.

The LEFT graph first: Greenhouse emissions reduce from IGCC to IGCC-Shift. They are higher for the UCG cases in the IGCC and IGCC-Shift but the IGCC-CO<sub>2</sub> has lower emissions for the UCG cases.

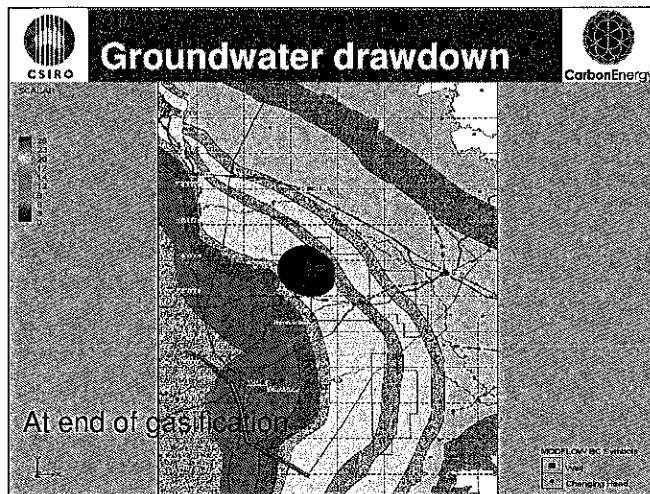
The RIGHT graph: UCG has significantly lower costs, generally only moderate electricity cost increase over conventional coal.



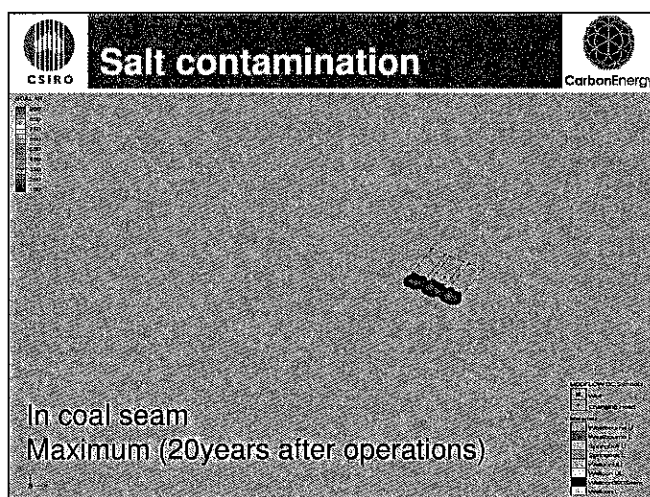
The modelling utilised CSIRO code COSFLOW and commercial codes MODFLOW & MT3D. The use of COSFLOW is critical due to the impact of disruption on permeability. These changes on a local basis are applied in a regional model to look at water draw and contamination. Besides the base case, the sensitivity to operating pressure and module design was examined.



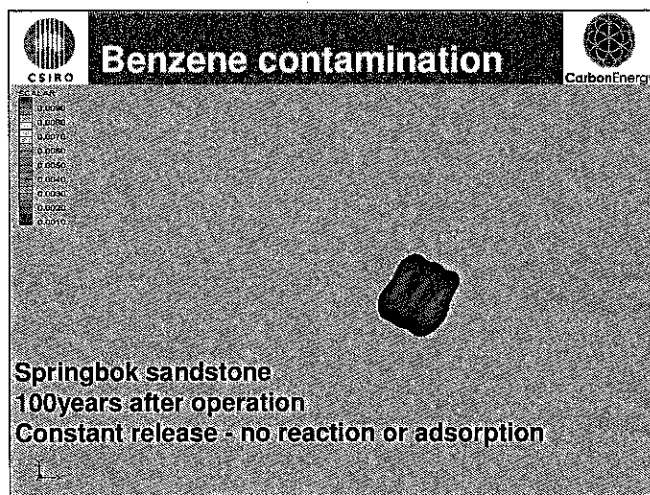
Maximum subsidence at surface around 0.5m, fairly trivial given the light land use at site.



The blue blob shows the extent of drawdown greater than 0.5m, which is regarded as insignificant even though it is over a 10km radius. Maximum drawdown of 17m (leaving 300+m) above UCG site. Even with exaggerated use of water during clean-up (not shown), the levels return to normal within 2.5 years. This is a lower impact than underground mining or CSM.



Pretty much negligible. The background salt concentration is fairly high.



This is a WORST case scenario – No real attempt at clean-up after operation and no organic removal due to reaction or adsorption. This shows contamination in the overlying aquifer, showing it links to the coal seam, but the levels of contamination are only of concern if there was drinking water in the aquifer (there is no reasonable quality water near this site). The spread is very slow and treatment could be started any time after operations ceased if it was detected and of concern. Treatment options include natural bacteria and air injection.

Public perception survey	
Issues raised by members of the public from the region after a discussion of the potential for UCG in the region	
Benefits of UCG	Prospective concerns
<ul style="list-style-type: none"> <li>❖ Better way of coal utilisation</li> <li>❖ Economic benefits</li> <li>❖ Environmentally beneficial</li> <li>❖ Benefits to regional community</li> </ul>	<ul style="list-style-type: none"> <li>❖ Safety</li> <li>❖ Environment</li> <li>❖ Cost</li> <li>❖ Information</li> <li>❖ Alternatives</li> <li>❖ Lack of trust in politicians, scientists &amp; business</li> </ul>

As a start on social engagement forums were held with CSIRO, Brisbane & Roma people to consider the benefits and concerns associated with UCG.

Only a brief explanation of UCG was given prior to the discussion.

This example is from Roma where, in general, they had more focus on local impact than the other groups.

CSIRO was the only group to express interest in GHG emissions.

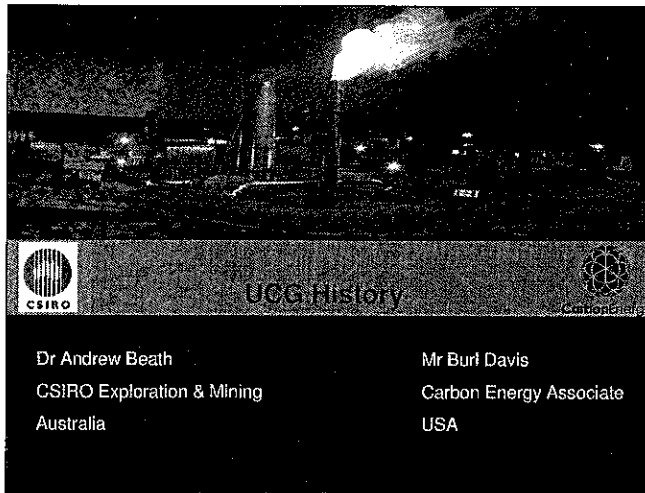
Summary of case study
<ul style="list-style-type: none"> <li>❖ Evaluated the Surat Basin for UCG sites</li> <li>❖ Modelled a 400MWe UCG power plant for: <ul style="list-style-type: none"> <li>o Comparative cost of electricity</li> <li>o GHG emissions</li> <li>o Environmental impacts <ul style="list-style-type: none"> <li>▪ Subsidence</li> <li>▪ Groundwater depletion and contamination</li> </ul> </li> </ul> </li> <li>❖ Examined public perceptions of UCG</li> </ul>

How does this relate to other sites?
<ul style="list-style-type: none"> <li>❖ Each site is unique, so all modelling must be repeated for the specific size of installation at the actual site</li> <li>❖ A general finding is that it appears possible to develop and environmentally sound and operationally efficient plants at suitable sites</li> </ul>

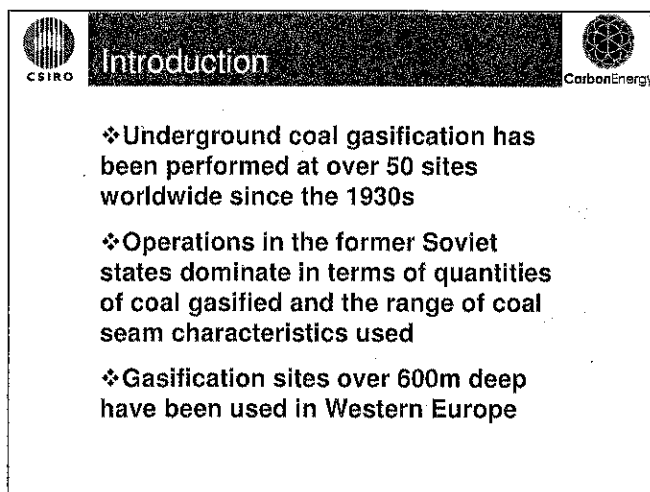
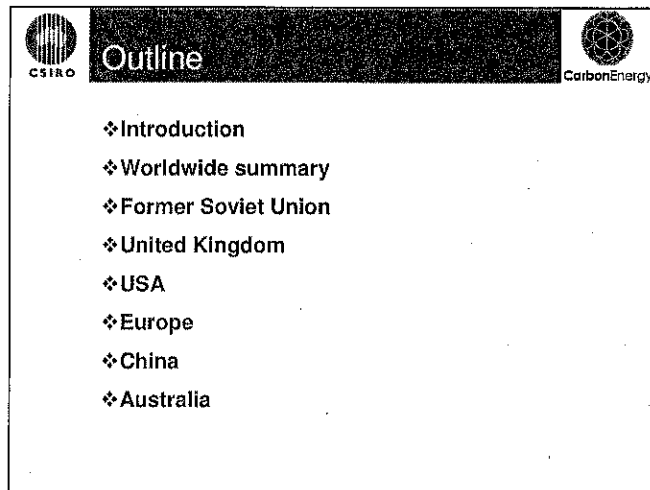


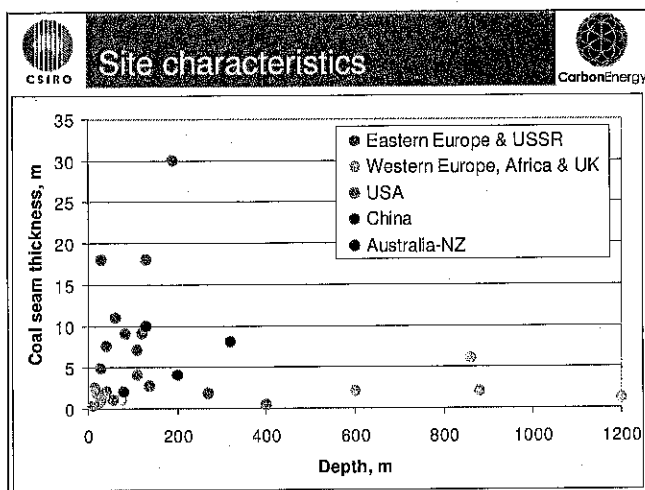
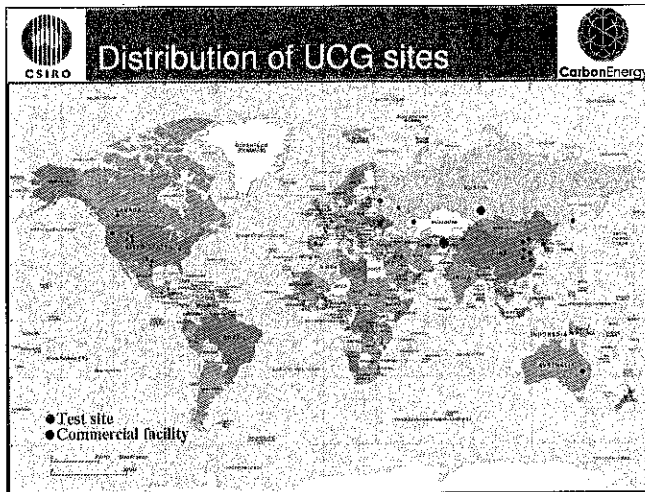
## 4. Additional presentation material

### History of UCG



UCG has a long and interesting history. This presentation broadly covers the worldwide development of the technology, but has special emphasis on the US government funded series of tests in the 1970s and 1980s. Mr Burt Davis worked on most of these tests and has provided a section of this presentation via Carbon Energy.





The use of shallow coal dominates the history of UCG, excepting the trials in Western Europe and Africa.

CSIRO is targeting deeper coal seams because we feel that more stable longer term operations are possible without problems with groundwater depletion. The operating pressure will also be in a more useful range for process operations.

Seams shallower than 100m are more likely to have problems than deeper seams. For example, excessive surface subsidence.

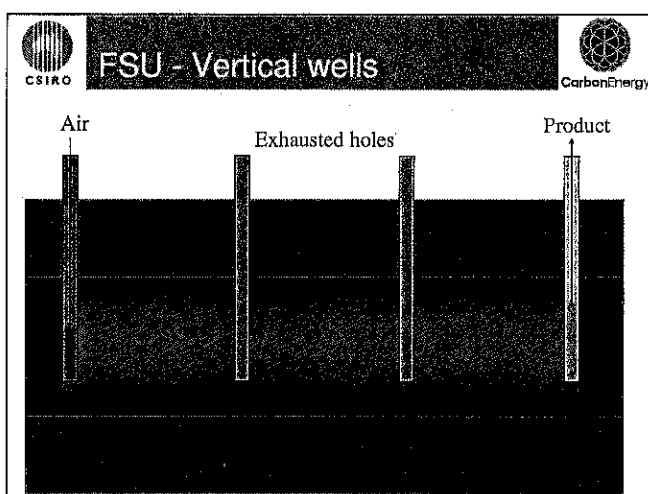
**Former Soviet Union**

- ❖ Research commenced in the 1930s with the target to demonstrate UCG in a wide range of coal seams
- ❖ Large plants were under construction prior to WWII, but were abandoned
- ❖ In the 1950s there was rapid expansion in use of UCG in many parts of the FSU
- ❖ Most plants closed with the increasing availability of Siberian natural gas
- ❖ Angren (Uzbekistan) and Yuzhno-Abinsk (Siberia) remain operational

CSIRO CarbonEnergy

### Summary of coal seam characteristics at Soviet UCG sites

Sites of UCG	Coal seam thickness, m	Depth of occurrence, m	Angle of dip, degree	Technical composition of coal			Low heat value, as received, MJ/Kg
				Moisture content as received,	Ash content, dry basis,	Volatile matter (Combustible mass)	
Liulelansk	0.44-2.0	60-250	15-30	12-15	7-17	39-40	20-23
Yuzhno-Abinskaya	2.2-9.0	30-300	55-63	2.5-8.0	2.3-5.2	27-32	28-30
<b>Brown coal</b>							
Angrenskaya	2.0-22.0	120-250	7-10	35.00	12.20	33.00	15.10
Podmoskovna	2.50	30-80	0-2	30.00	34.30	44.50	11.80
Shatsk	2.6-4.0	30-60	0-2	30.00	26.00	38.10	11.10
Snezhkovsky	3.5-6.0	80.00	0-2	35.00	23.80	64.50	8.00




Used in many Soviet operations, early USA trials and the recent Australian trial by Linc Energy

Simple to construct and operate


Well documented and has been used in large operations (eg. Angren with 5+ million tonnes of coal gasified)

Becomes expensive when used with deeper coal due to excessive drilling requirements




CSIRO

## United Kingdom (UK)




CarbonEnergy

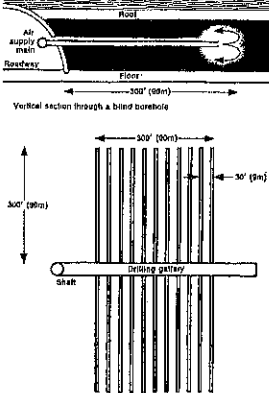
- ❖ First UCG test was at Durham in 1912 and a full research programme ran from 1949-1959 to develop a commercial industry
- ❖ Commercial trials performed from 1956-1959 to develop a power generation site (unsuccessful, but the last trial performed well)
- ❖ Reviews in 1964 and 1976 to decide if research should be continued
- ❖ New research programme started in 1999




## UK – Newman Spinney (1958)




- ❖ Blindhole layout gave the best performance during the experimental trials
- ❖ Problems were experienced with the injection pipes failing during operation

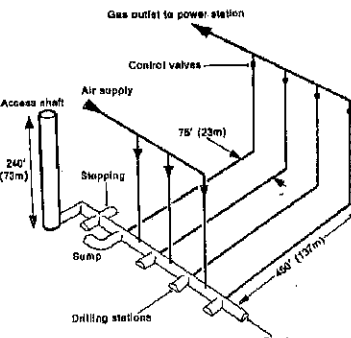


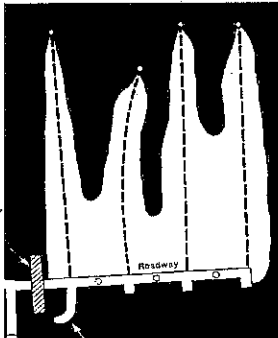


## UK – Newman Spinney (1958)



**Final commercial design and cavity formed in trial**







## UK – Recent developments



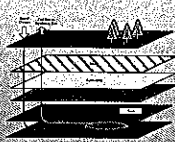
- ❖ New research programme commenced in 1999 to evaluate the potential of UCG to replace North Sea natural gas
- ❖ Most research has been on site selection, drilling technology, cost evaluation and environmental criteria
- ❖ Drilling and in-situ gasification trials have been delayed and now require industry support
- ❖ A feasibility analysis has been produced for a proposed site at the Firth of Forth

## History of UCG in the U.S.A

By

Burl E. Davis

Carbon Energy Associate



### HISTORY OF UCG in the United

**States**, by Burl E. Davis, Carbon Energy Associate and former technical director of the Rawlins, RM-1, and Huntley 5-spot in New Zealand

During the past thirty-five years, there have been significant developments in Underground Coal Gasification technology in the United States. Government-funded programs have focused on the development of two process configurations -- the Controlled Retracting Injection Point (CRIP) and the Steeply Dipping Bed (SDB). Private industry has participated in these programs and is continuing its activities in the development and commercialization of these technologies.

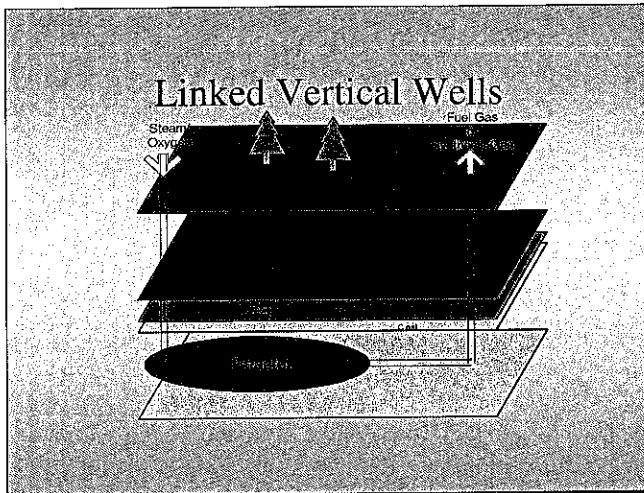
### U.S. Department of Energy Programs

Date	Organ.	Location	Process Config.	Coal Rank	Seam Thick.	Seam Depth
1971-1981	Laramie EIC	Hanna, WY	LVW-RCL	Sub.	7M	80M
1972-1982	Lawrence Livermore	Hoe Creek	LVW-RCL	Sub.	5M	30M
1977-1980	Morgantown WV	Pricetown WV	LVW-drilled link	Bit.	3m	300m
1976-1982	Gulf/DOE	Rawlins	SDB	Sub.	7m	120-200m
1981-1985	Lawrence Livermore	Centralla, Wash.	CRIP	Sub.	4-8m	20-50m
1986-1993	Ind.Cons/D OE	Hanna, WY	LVW-CRIP	Sub.	7m	75m

The U.S. Government program supported 5 major field test programs and the development of supporting technology.

### U. S. Industrial UCG Projects

Date	Organization	Location	Proc. Config.	Coal Rank
1978-80	Texas A&M	Rockdale TX	LVW-RCL	Lignite
1976-80	Texas Utilities	Tennessee Colony	LVW	Lignite
1977-82	ARCO	Rocky Hill WY	LVW-RCL	Sub.



LVW was the basic configuration of the first tests in the U.S.

Early results at Hanna demonstrated the potential of vertical wells spaced about 20 meters apart with linking between the wells by Reverse Combustion Linking. Data from Hanna II demonstrated that RCL produced multiple channels during the linking by reverse combustion with only one being completed. Once linking was established and forward gasification initiated, the reactor grew upward and along the centerline between the point of injection of the combustion gas and the removal of the product gas at the base of the production well taking a teardrop shape. This was the case no matter what the path of the completed link.

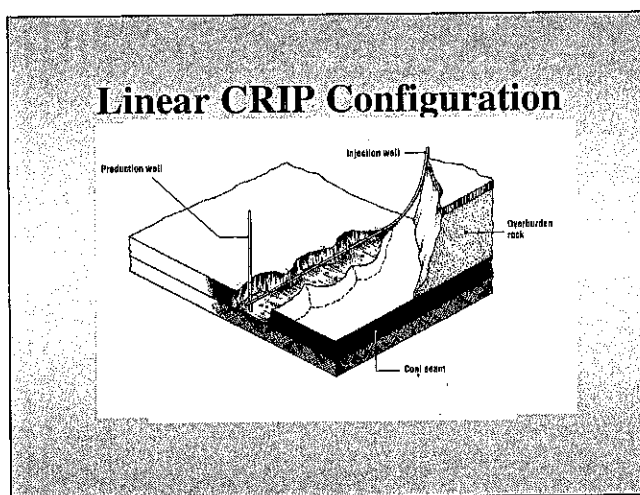
However, when the process was attempted at a less ideal site at Hoe Creek, there were problems with maintaining process between the along the center line between process wells and the reactor moved to the roof of the seam and actually gasified some coal from a second seam overlying the target seam. When the injection well casing burned to the top of the seam the reactor actually moved to an overlying seam when the weak roof failed. Although Hoe Creek was a site that was too shallow with an extremely weak roof causing subsidence reaching the surface, knowledge gained there demonstrated the need for a positive linking mechanism such as directionally drilled boreholes between the process wells and greater emphasis on maintaining the oxidant injection and product gas removal low in the seam.

Both Hanna and Hoe Creek experienced high temperatures near the life of the modules. This was due to burnout of the coal at the base of the injection well and oxygen being seen at the product well. Lawrence Livermore proposed a concept that would cause the injected oxidant (air or oxygen) to contact fresh coal. This involved drawing the oxidant injection point back into fresh coal with drilled boreholes connecting the process wells. The mechanism was termed Controlled Retracting Injecting Point (CRIP). The concept was developed into a process in a series of tests at the Tona site in southern Washington culminating with the Partial Seam CRIP test in 1984. The effectiveness of the linear CRIP configuration tested at Tono is still hampered with the dealing with a product gases sweeping through a continually growing reactor volume.

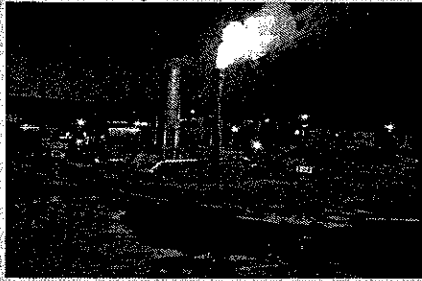
## Hoe Creek Findings

**Directional Drilling as the primary method of linking.**

**Importance of maintaining gas flow low in the seam.**



## Rocky Mountain -1



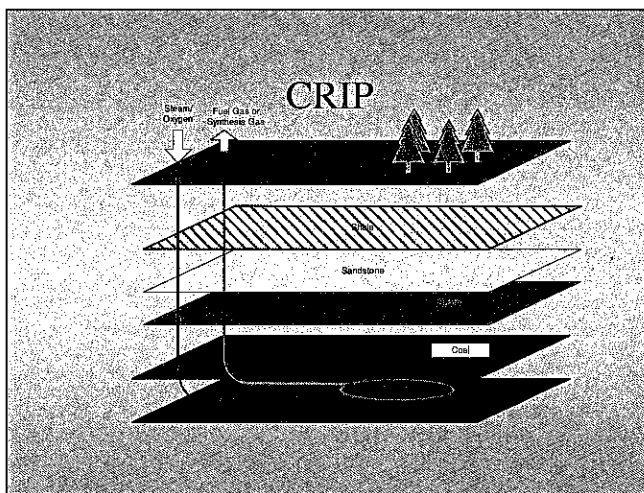
Rocky Mountain 1 was the last of the DOE programs. It was funded jointly by the DOE and an industrial consortium led by the Gas Research Institute. The technical team consisted of staff of Lawrence Livermore, Western Research Institute, UNDERC, and Energy International, (the Gulf technical team from Rawlins).

## Rocky Mountain 1

- **Operation of parallel reactors**
  - LVW
  - CRIP
- **Steam/Oxygen**
- **Slip Stream Catalyst Test**
- **Full Environmental Compliance**

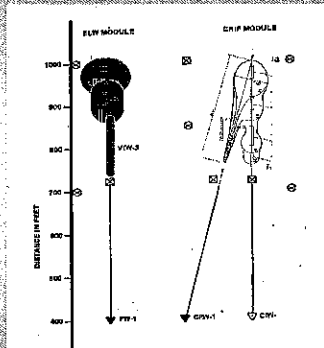
RM-1 consisted of two UCG reactors in the same horizontal subbituminous coal seam as the Hanna test series. One of the primary objectives was to demonstrate the CRIP (Controlled Retracting Injection Point) reactor process and compare it to a horizontal reactor consisting of a drilled link product well and a vertically drilled steam/oxygen injection well. In addition to process evaluations, extensive environmental studies and product gas upgrading studies were performed during the test period of 100 days.

In addition to process evaluations, extensive environmental studies and product gas upgrading studies were performed during the test period of 100 days.



Instead of the linear CRIP, the RM-1 configuration utilized directionally drilled horizontal wells forming a "V" shaped pattern with the apex at defined with a vertical process well to support startup operations. When ignited the reactor grew up-dip from the junction of the process wells.

## Rocky Mountain 1



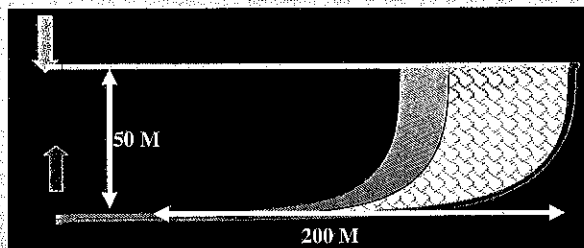
## Test Results

- |   |   |
|---|---|
| <ul style="list-style-type: none"> <li>• <b>LVW</b> <ul style="list-style-type: none"> <li>- 65 Days to Burnout</li> <li>- Second Injection Well</li> <li>- 70-100 Tons/day</li> <li>- HHV 230-280 Btu/scf</li> </ul> </li> </ul> | <ul style="list-style-type: none"> <li>• <b>CRIP</b> <ul style="list-style-type: none"> <li>- 90 Days of Operation</li> <li>- 4 Reactors</li> <li>- 70-200 Tons/day</li> <li>- HHV 250-320 Btu/scf</li> </ul> </li> </ul> |
|---|---|

The LVW operated as expected in the forward gasification mode with burnout occurring when the reactor shape/volume reach the size that the primary oxidation reaction zone reached the product well casing shoe. The LVW burned out in 65 days shutdown when oxygen was detected in the product gas (0.5 %).

The CRIP process demonstration produced gas of approximately 300 Btu/SCF and met all technical objectives of the program. The CRIP maneuver was successfully performed 3 times during the program as per the original schedule. The test was terminated when all of the technical objectives were achieved. After shutdown, the site was restored to pretest conditions with full compliance with environmental requirements and the site abandoned.

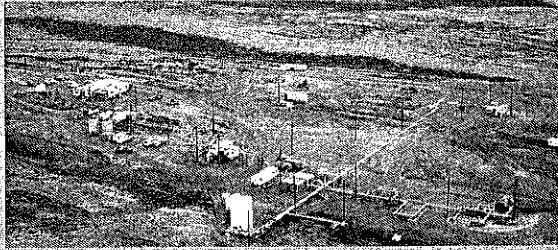
## CRIP Reactor Development (Plan View)



The CRIP module operated as a streaming gasifier sweeping along the coalface between the injection well and the product well. The effective reactor volume reached an equilibrium level with the reaction bypassing the spent portion of the reactor. At shutdown, the product gas was of good quality.



## Rawlins



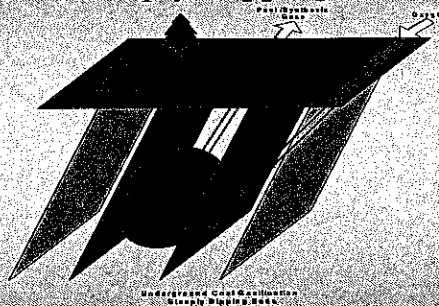
Russian technology used at Yuhzno-Abisk in Siberia in bituminous coal considered to be some of the more successful of Russian UCG facilities. The DOE felt that this technology should be a part of the U.S. program. The DOE solicited proposals from industry for this part of the DOE program. Gulf Oil was the successful bidder for the cost shared project. An extensive study of the U.S. steeply dipping coal reserves was performed to select a site meeting rigorous technical and environmental criteria. Identified the steeply dipping seams just west of Rawlins Wyoming in the Continental Divide Basin as the lowest risk site for both environmental and technical concerns.

Tests were performed in 1979 primarily with air and 1981 with steam oxygen in the steeply dipping seams of subbituminous coal dipping at 60° with a thickness of 7-8 meters. This was the first test in the DOE program to operate within the full permitting requirements of the Wyoming Department of Environmental Quality.

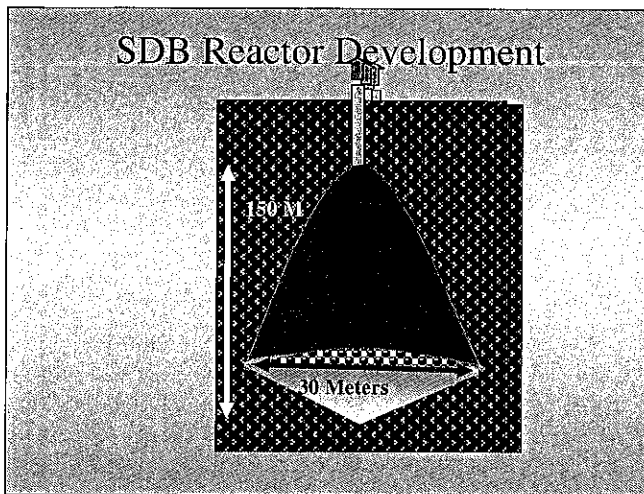
## Rawlins

- Two Tests
- Gulf Oil Cost Shared Contract
- Subbituminous Coal
- 7-8 Meters Thick
- Seam Dip 60°
- Full Environmental Compliance

## Steeply Dipping

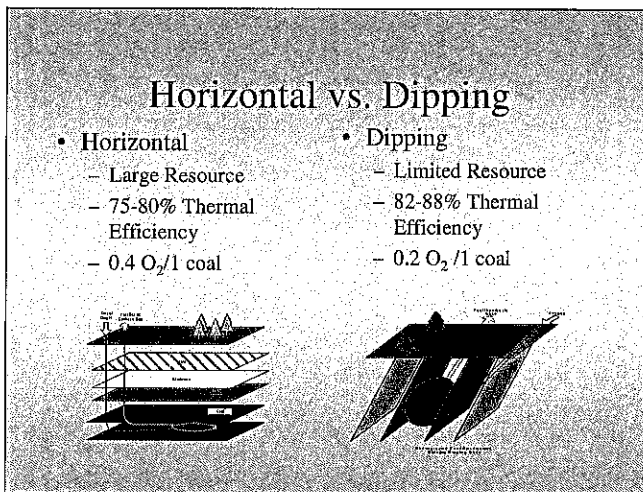


Unlike the Russian parallel well configuration in steeply dipping in bituminous (agglomerating) coal, the well configuration utilized footwall entry wells for both process wells. Footwall entry assures that the reactor will remain low in the seam and avoid disruption of process gas flow because of well failure from subsidence. The 1981 test employed as second vertical injection well 10 meters across the seam. This well was linked to the active reactor and operated as a second reactor to about 10 days. The gas quality from this reactor was considerably poorer than for the footwall injection reactor due to the contact of the reactor with the roof of the seam. After the 1981 experimental program was completed, the site was shutdown and monitored for subsidence and groundwater contamination. No movement of the overlying strata or surface was detected and the groundwater was declared restored after 5 years and the site abandoned.

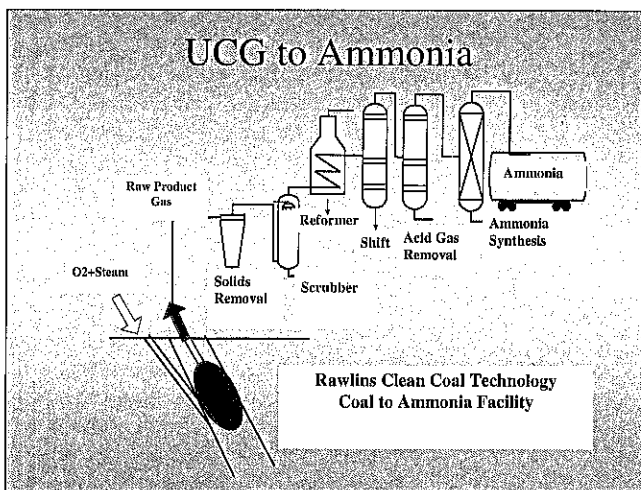


Once the seam was ignited at the base of the footwall injection well, the hot gasses flowed to the product well drying the coal and causing it to fall to the base of the reactor. Relative quickly, a molten slag pool collected at the point of injection of the oxidant. There is considerable evidence that the primary exothermic reaction of oxygen with the carbon occurred in the molten slag raising it to temperatures in excess of 1200° C. As the reactor grew, the coal fell from above the reactor into the bed with the reduction and pyrolyzed in the bed similar to a Lurgi slagging gasifier.

Any fall of the overlying sandstone strata occurred after the process was shut down and the reactor void was cooling.



Comparison of the results of RM-1 CRIP is important. Clearly the steeply dipping configuration is the more efficient process with higher gas quality, better thermal efficiency, and better yield of product per unit of oxidant. However, the amount of steeply dipping coal resources is considerably less than horizontal. Additionally, the formation of dipping reserves causes considerable fracturing of the coal seam, which can make it difficult to maintain reactor integrity, which increases environmental problems. The Rawlins resource was a special case and it is unlikely that many steeply dipping reserves like that exist.



Energy International was awarded a Cooperative Agreement as a part of Round One of the 1986 DOE Clean Coal Technology program. Energy International was a spin-off of the Gulf/Chevron merger consisting of largely the Gulf Rawlins technical team. EI proposed to move an existing plant to the Rawlins site for the production of 400 tons/day of anhydrous ammonia. The plant would utilize synthesis gas generated by in-situ gasification of the steeply dipping resource at the site of the Gulf-DOE demonstration program of 1977-1982.

## Conclusions

Each DOE UCG Program contributed to the evolution of UCG Technology

Results were published and available to other workers in the field

Virtually all of the technology is considered a the public domain

Each of these programs contributed to the evolution of UCG technology to the state that it is today. The detailed results of these programs were published and presented in a number of technical meetings and journals during the time period of 1970 to 1990. Much of the technical findings have contributed to advances in UCG technology around the world with virtually all of the technology considered in the public domain.



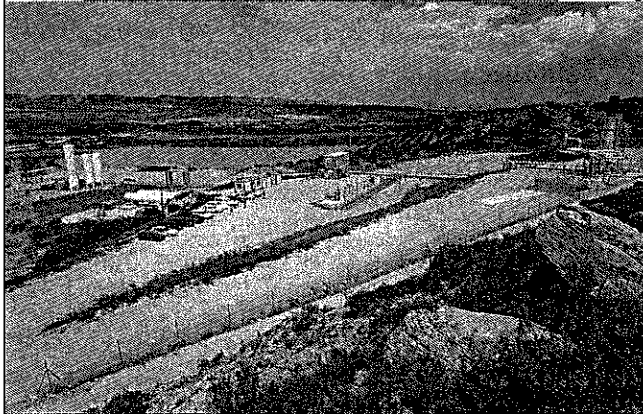
### Europe



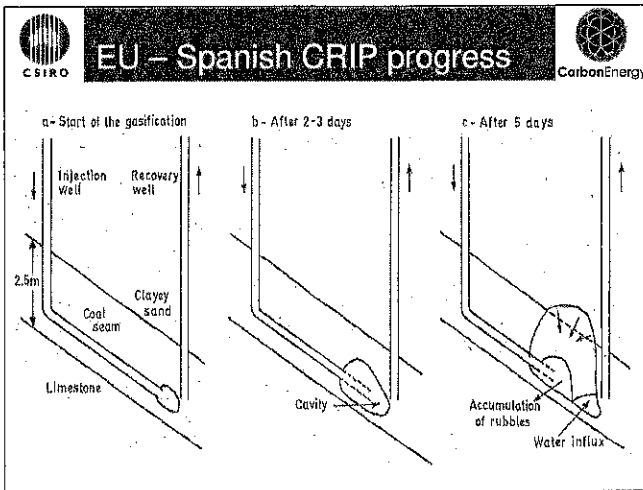
- ❖ Experimental trials have been held intermittently since 1948 in Western Europe in deep coals
- ❖ Recent notable trials have been at
  - o Thulin (1982-84 and 1985-86) in Belgium
  - o Alcorisa (1997) in Spain
- ❖ The recent trials have benefited from the use of CRIP technology as this is more suited to use in deep coal seams than vertical wells



### EU - Spanish Test Site



Coal seam was at approximately 600m depth and a linear CRIP technique was used.



**EU – Spanish summary**

- ❖ Coal seam ~2m thick at ~600m
- ❖ Oxygen and liquid water injection
- ❖ Operations hampered by high water production (wet sand overburden)
- ❖ Injection well failed structurally
- ❖ Construction and operation problems relating to poor site characterisation and selection

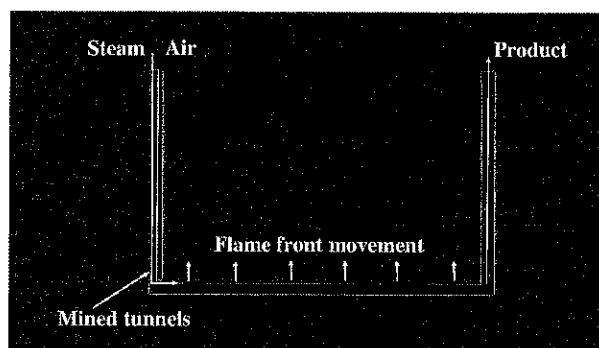
**China - Introduction**

- ❖ China has developed a different technique using mined tunnels and has demonstrated it at least 12 sites since 1995
- ❖ Air and steam are used, sometimes in stages, to produce either fuel gas, synthesis gas or hydrogen
- ❖ While high quality gas can be produced using the technique, the economics are difficult to evaluate because most plants receive 5-year grants to aid construction and none have been expanded after the 5-year period

Almost all of the sites are now closed, but a new development in Mongolia has been announced that appears to be using Soviet technology supplied by the Angren operators.



## China – Tunnel technique



## China – UCG usage



❖ Product gas from China's UCG sites has been used for various purposes, including:

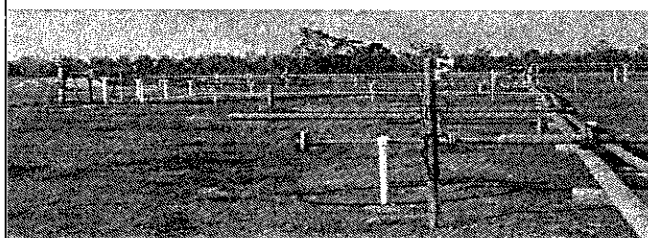
- o Domestic fuel gas
- o Coal-fired boilers
- o Pottery kilns
- o Ammonia synthesis



## Australia – Linc Energy



- ❖ Trial operated at Chinchilla from 1999 to 2002
- ❖ Over 30,000 tonnes of coal used in 2 gasifiers
- ❖ 10m thick seam at 130m depth using a modified vertical wells technique





## Australia – Linc Energy



❖ Linc Energy had a successful share offering earlier in 2006, raising \$22million

❖ Development of a small liquid synthesis plant is planned at the same site as the earlier demonstration with the support of Syntroleum, a Fischer-Tropsch technology provider



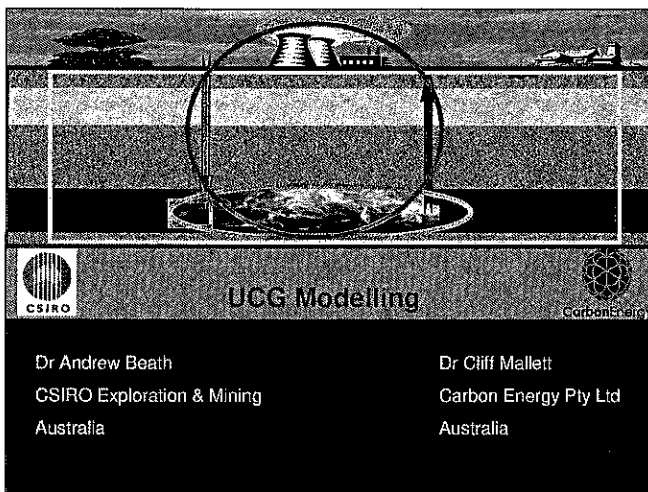
The End



Dr Andrew Beath  
CSIRO Exploration & Mining  
Australia

Mr Burl Davis  
Carbon Energy Associate  
USA

## Modelling of UCG



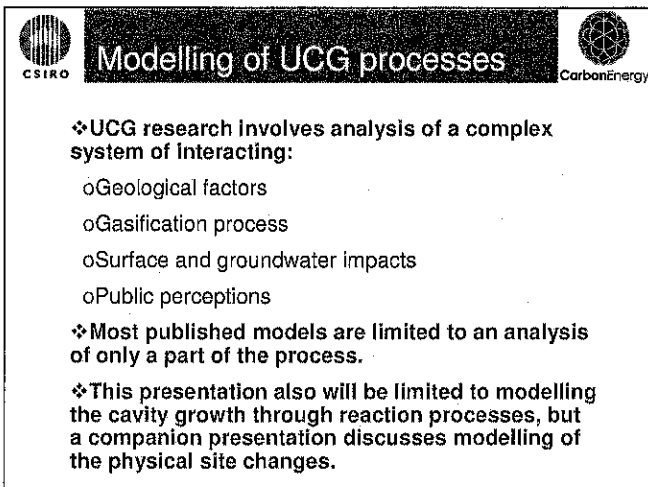
The slide features a background image of a UCG site with a large circular wellhead and industrial structures. The title "UCG Modelling" is centered. Logos for CSIRO and CarbonEnergy are on the left and right respectively. Below the title, the names and affiliations of the presenters are listed.

**UCG Modelling**

Dr Andrew Beath  
CSIRO Exploration & Mining  
Australia

Dr Cliff Mallett  
Carbon Energy Pty Ltd  
Australia

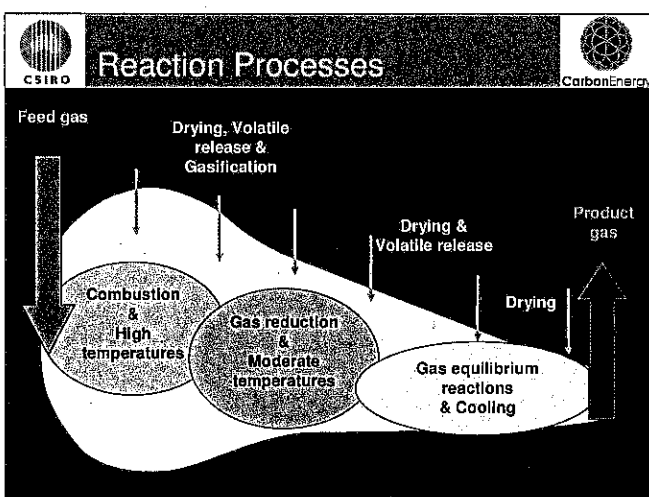
It is difficult to accurately predict the behaviour of UCG sites, largely because of uncertainty about the geology but also because of the complexity of the interactions between reactions and site characteristics. This presentation reviews the factors involved and some of the modelling work that has been performed in this area.



The slide has a dark header with the title "Modelling of UCG processes" and logos for CSIRO and CarbonEnergy. The main content is a list of bullet points describing the complexity of UCG research and the limitations of current models.

**Modelling of UCG processes**

- ❖ UCG research involves analysis of a complex system of interacting:
  - o Geological factors
  - o Gasification process
  - o Surface and groundwater impacts
  - o Public perceptions
- ❖ Most published models are limited to an analysis of only a part of the process.
- ❖ This presentation also will be limited to modelling the cavity growth through reaction processes, but a companion presentation discusses modelling of the physical site changes.



Coal & char reactions  
Coal/char structural changes  
Gas flow and reactions  
Water flows and evaporation  
Heat transfer  
Conduction, convection & radiation  
Rock & coal breakage and collapse  
Resizing of the matrix with growth



## Literature models



- ❖ **Selected published models**
  - o CAVSIM (Lawrence Livermore)
  - o CFD (Delft Univ. of Technology)
  - o Box (European Community)
- ❖ **Numerous 1-dimensional models have been published with relatively minor differences**



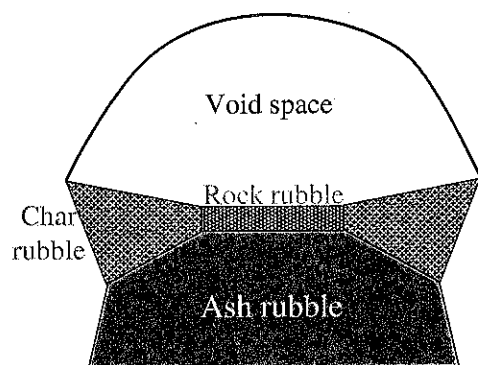
## CAVSIM-Lawrence Livermore



- ❖ **Assumes the gasification cavity will be axisymmetrical around a vertical axis**
- ❖ **Developed to model CRIP experiments performed in the USA**
- ❖ **Limited reaction set, heat transfer and gas flow**
- ❖ **Cavity growth is by 'spalling', where material falls off the roof and walls**



## CAVSIM geometry







## CAVSIM summary



CAVSIM was used successfully to model specific experiments, but was hindered by the difficulty in estimating the 'spalling' rate until after the experiment was performed and required corrections when the geometry was disturbed by shortening of the CRIP



## CFD-Delft Univ. of Technology



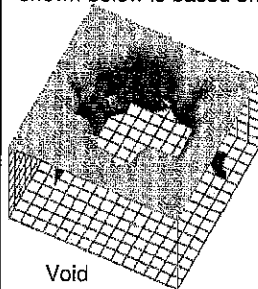
- ❖ Series of models developed for the European Community gasification trials
- ❖ Considered the site as being composed of numerous finite elements of coal that increased in porosity with reaction
- ❖ Simplifying assumptions include constant block temperature and pre-defined gas flow path, but vary between model versions



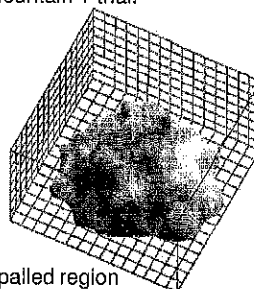
## Delft example



Biezen (1996) produced a model which allowed collapse of material when the porosity becomes excessive. Some factors require fitting to experimental data. The example shown below is based on the Rocky Mountain 1 trial.



Void



Ash/Spalled region



## Delft summary



The Delft approach is extremely numerically intensive. Several different models have been published, but they all require simplifying assumptions to allow solutions to be achieved. For example, an average temperature may be used for all coal in the region of the void.



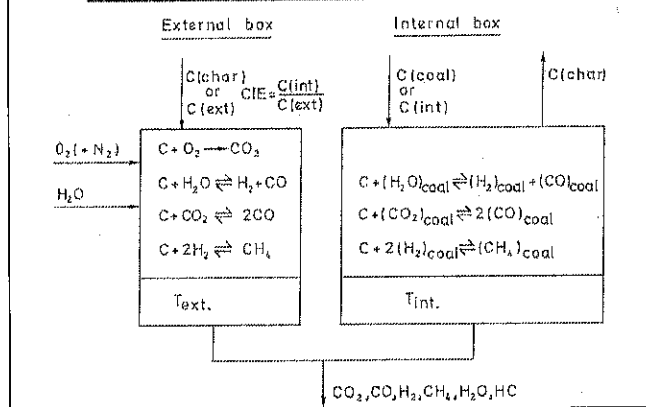
## Box models-European Comm.





- ❖ Simplified models that involve zones with pre-defined roles, for example:
  - o First box is a combustion zone
  - o Second box has other gasification reactions
  - o Third box allows gas bypass of reactions
- ❖ Generally, the product gas is assumed to be at equilibrium at an assumed exit temperature





## 2-Box model (Dufaux, 1990)



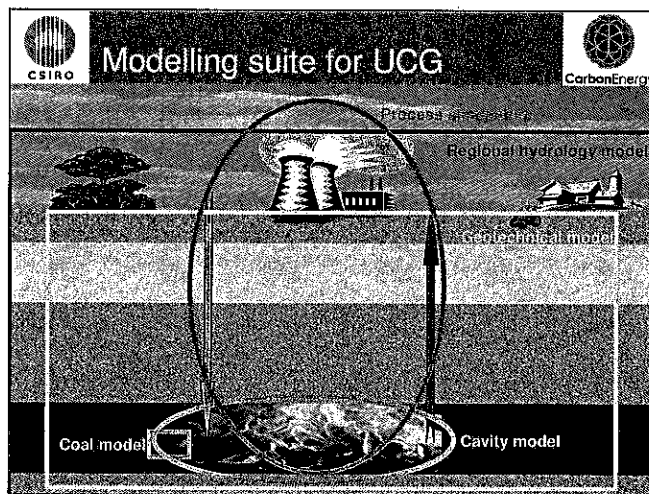
## Box model comments

- ❖ This type of modified equilibrium model is useful for rapid predictions
- ❖ Definition of the boxes is fairly arbitrary and can vary with gasification technique and site characteristics
- ❖ There is a tendency to increase the number of boxes to improve alignment with experimental results, but this makes it more a correlation than a model

## CSIRO modelling

We have taken a more comprehensive approach to UCG, considering not only the gasification process but also the geotechnical and hydrology interactions. This requires a suite of models, rather than a single model.



Report also included legislative requirements (related to social perceptions), but there is little applicable legislation if the groundwater is not suitable for human consumption.



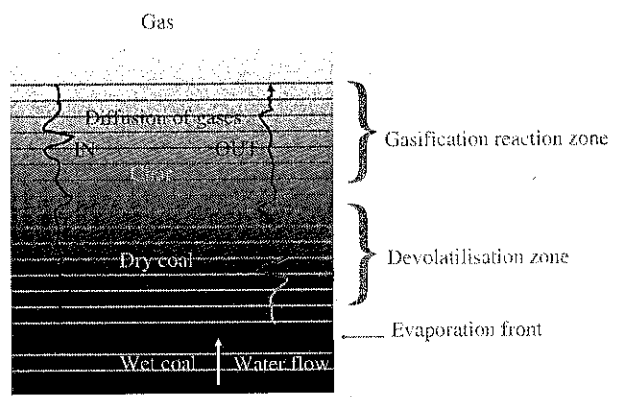
## Elements of the Coal & Cavity models for UCG



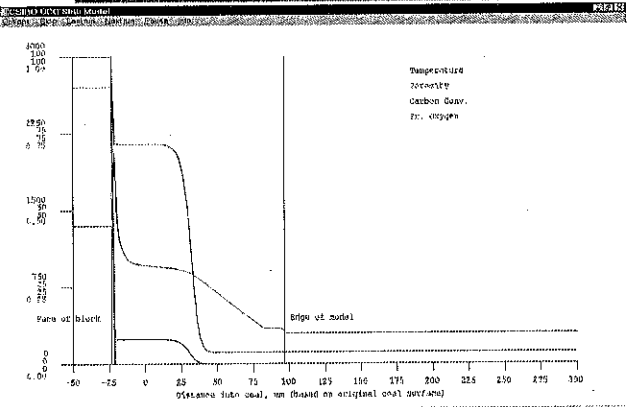
- ❖ Coal & char reactions
- ❖ Coal/char structural changes
- ❖ Gas flow and reactions
- ❖ Water flows and evaporation
- ❖ Heat transfer
  - Conduction, convection & radiation
- ❖ Rock & coal breakage and collapse
- ❖ Resizing of the matrix with growth

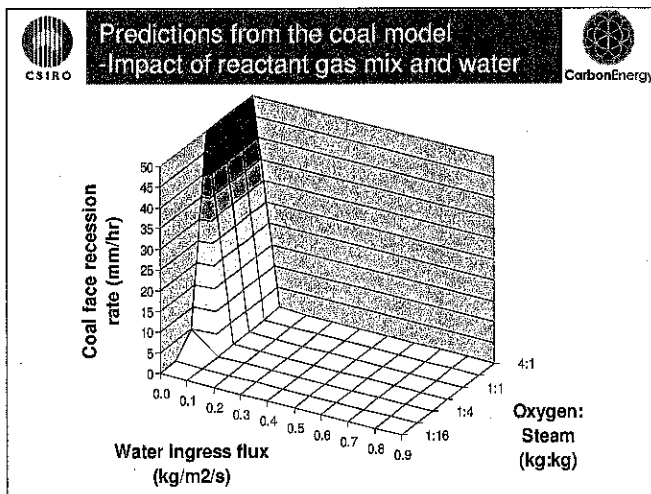


## Coal model

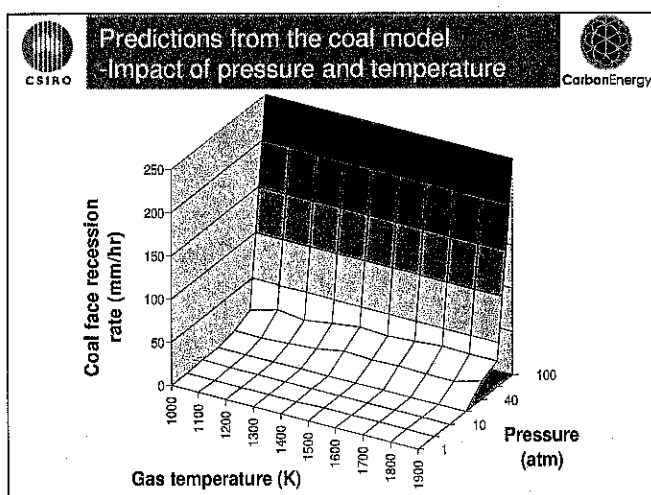


## Output from coal model





Examples of predictions showing the influence of water and oxygen availability on coal reaction rate.

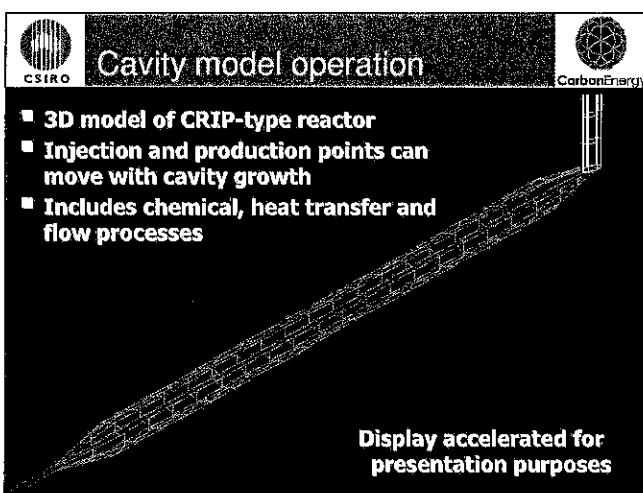
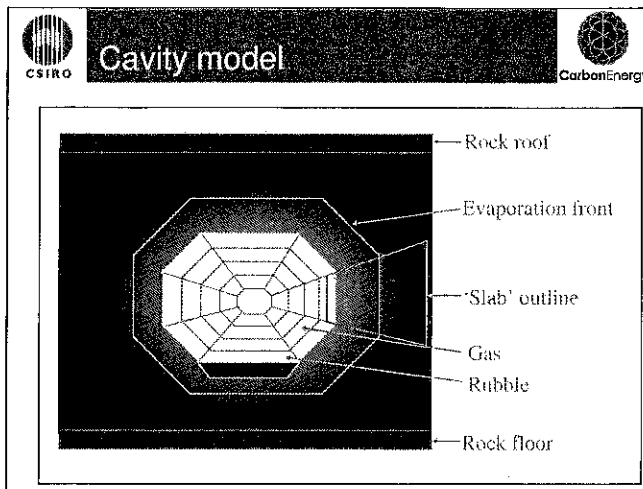


Examples of predictions showing the influence of gas temperature and pressure on coal reaction rate.

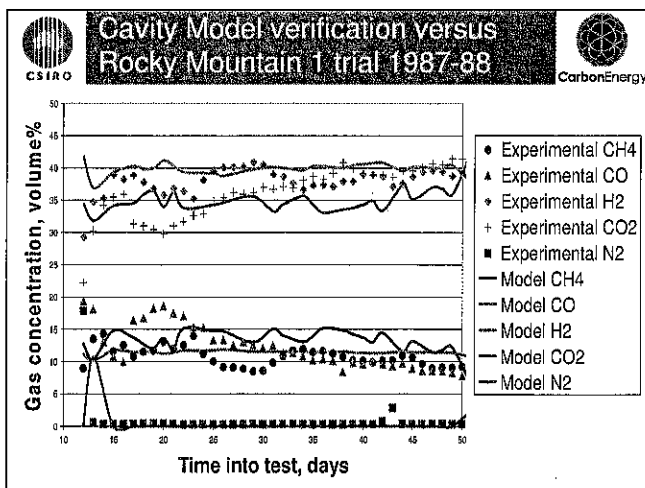
**Use of the coal model**

- ❖ Does not provide standalone predictions relevant to UCG as it neglects many of the gas flow and heat transfer features of real cavities
- ❖ Makes spot predictions of coal behaviour under pseudo-steady state conditions to feed into more complex models
- ❖ Can be used to predict the general operating regimes that are desirable for efficient gasification

Logos: CSIRO, CarbonEnergy



The model can predict the performance of sites of different characteristics and using different UCG designs. The design shown is the single CRIP reactor used in some USA and Western Europe trials.





## Model performance



### Predicts accurately:

- o Cavity volume changes
- o Product gas composition and flow

### Hindrances to model performance:

- o Requires detailed site information
- o Experimentally, the cavity shape was affected by uncontrolled shortening of the 'CRIP' and an undetected fault running through the site



## Other models



❖ Geotechnical - COSFLOW is a CSIRO developed model for rock collapse, water flow, contaminant flow and gas flow in mining affected strata.

❖ Regional hydrology – MODFLOW is a public domain modelling platform for large scale hydrological simulation.

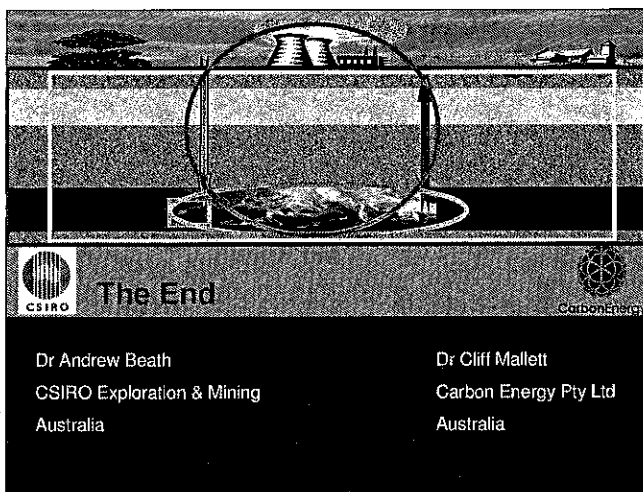
❖ Process simulation – HYSYS.Process is commercial software package that can be used to simulate power production and chemical production from UCG product gas.



## Summary

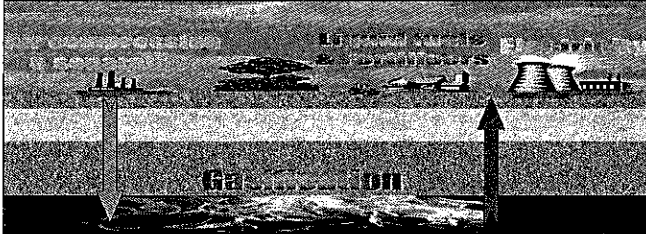


There have been numerous published models relating to UCG, however, it is apparent that the interaction of the underground reactions with the geological 'container' requires a more comprehensive approach that includes the





## Power process simulation




**Power Process Simulation**


CSIRO CarbonEnergy

Dr Andrew Beath	Dr Cliff Mallett
CSIRO Exploration & Mining	Carbon Energy Pty Ltd
Australia	Australia


The product gas from UCG is generally not a saleable product, so it is important to see how efficiently it can be used in an overall process incorporating UCG. The most straight-forward utilisation that can be compared with alternative processes is power generation




**Outline**




- ❖ Power generation by boiler and gas turbine plants
- ❖ Simulation of modern combined cycle power plants
- ❖ Comparison of Greenhouse emissions and electricity costs with other common power systems



**Power generation using UCG - Boiler plant**




- ❖ UCG has had a long history of use in providing supplementary fuel gas for use in coal-fired boilers in the Former Soviet Union
- ❖ The low radiant properties of the gas mean that usage is restricted to approximately 30% of the total fuel or a boiler designed for gas is required
- ❖ Only rudimentary cleaning of the gas is required to prevent fouling of pipework




## Power generation using UCG


### - Gas turbine plant



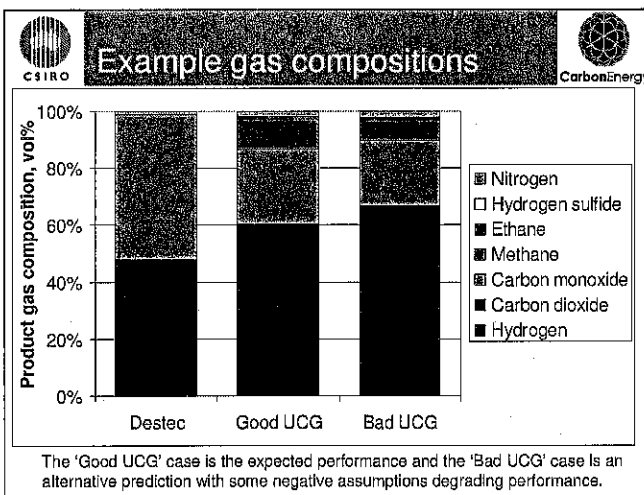
- ❖ Advances in the design and construction of gas turbines means that there are now turbines available that can operate on gas from coal gasifiers, including UCG
- ❖ Combined cycle plants incorporating gas and steam turbines can provide high efficiency power generation from UCG



## UCG and gas turbines



- ❖ UCG product gas has a different composition for every site and varies significantly from that of entrained flow gasifiers for IGCC systems
- ❖ This has an impact on the design of the turbine combustor and the turbine
- ❖ Turbines are typically specified on mass flow, so the different gas composition can impact on operation



The Destec figures are from a study of an IGCC system with an entrained flow gasifier.

Good UCG is a conservative base case, while Bad UCG has exaggerated heat loss and water inflow.

The higher CO<sub>2</sub> of the UCG gases is misleading – the UCG cases have C:H of about 0.62 versus 0.75 for the Destec case, arising from char left in the ground and tar that is removed from the gas.

Significant differences in the processes are in the consumption of oxygen and the density of the product gas.



Process	Feed gas
Gas turbine combined cycle (IGCC)	Surface coal gasifier (Destec)
IGCC with CO <sub>2</sub> removal (IGCC-CO <sub>2</sub> )	UCG base case (Good UCG)
IGCC with Shift and Removal (IGCC-Shift)	UCG "worst" case estimate (Bad UCG)

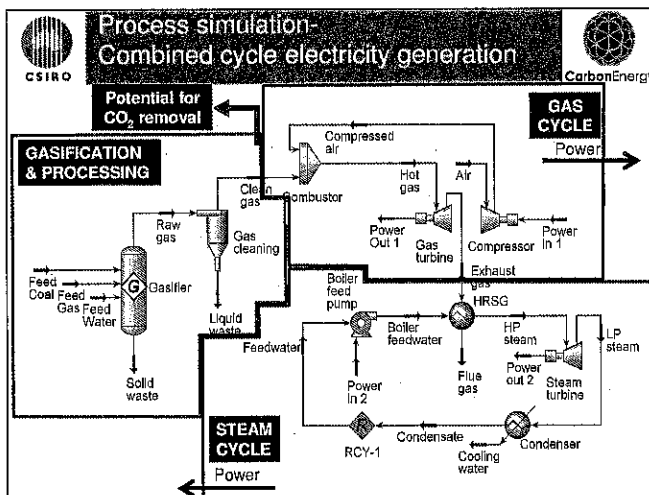
**Note: All processes use commercially available technologies**

Processes simulated using a combination of HYSYS.Process in-built modules and CSIRO models for specialised components (eg. UCG, CO<sub>2</sub> removal and Shift reactors).

Costing based on NETL (2001) publications and CSIRO costing, with electricity cost using EPRI levelised costing.

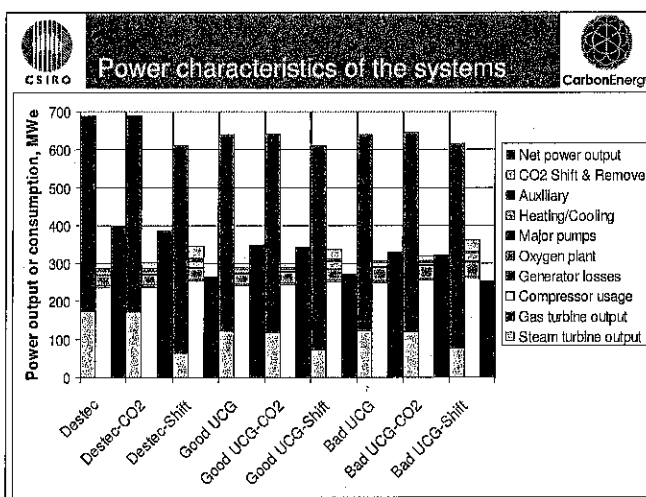
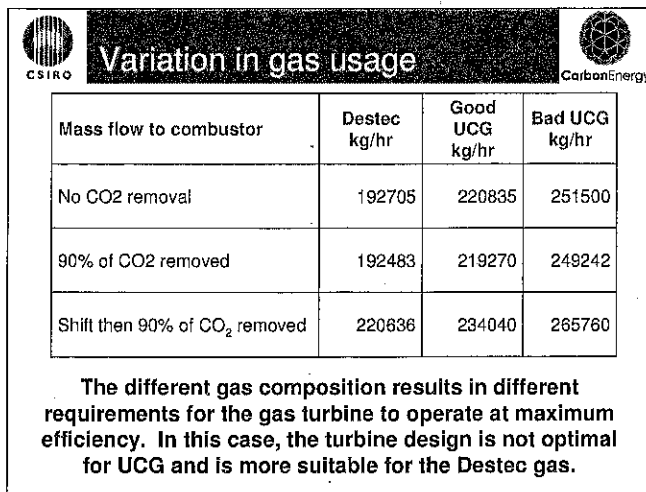


- ❖ **HYSYS.Process**, a commercial software package, is used for the basic power system modelling
- ❖ A specialised module was developed in **HYSYS.Process** to provide coal gasification performance input to the simulation
- ❖ Carbon dioxide removal and shift reactor performance were determined in a separate model

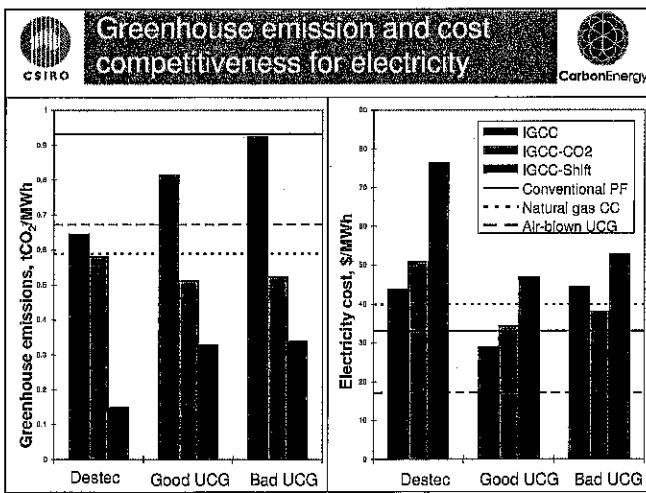


This is a standard IGCC type process using UCG product gas. Modifications to this process to incorporate carbon removal for sequestration have been considered.

We have also looked at the process rearrangements required to utilise the product gas in Gas To Liquids processes to produce synthetic liquid fuels



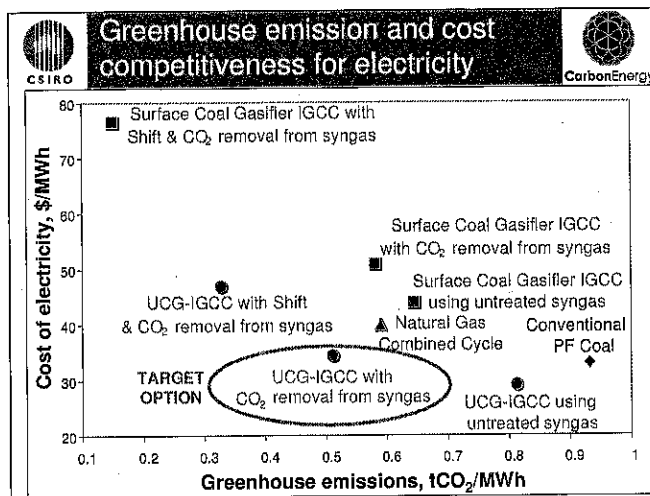
There are differences in both the gross power production and internal power utilisation for the different processes.



The three different processes are shown as different colours, the different feed gases are on the X axis. Lines are from CISS and other CSIRO studies. The air-blown UCG numbers are based on the Linc Energy trial at Chinchilla and are better than the oxygen-blown if CO<sub>2</sub> removal is not considered.

The LEFT graph first: Greenhouse emissions reduce from IGCC to IGCC-Shift. They are higher for the UCG cases in the IGCC and IGCC-Shift but the IGCC-CO<sub>2</sub> has lower emissions for the UCG cases.

The RIGHT graph: UCG has significantly lower costs, generally only moderate electricity cost increase over conventional coal.



UCG product with carbon dioxide removal and then combined cycle gas turbine power generation is the most attractive option in terms of reducing Greenhouse emissions without dramatically increasing the cost of electricity. Carbon dioxide sequestration costs are not included in the analysis, but it appears to have a quite favourable performance compared to other coal-fired options.

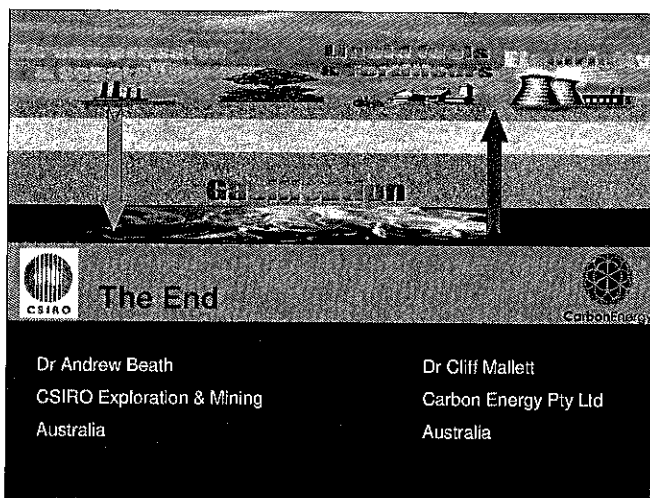
**Approximate efficiencies for different generation processes**

Process	Efficiency
Air-blown UCG	45.4 %
Oxygen-blown UCG	46.5 %
UCG with CO <sub>2</sub> separation	39.8 %
Conventional coal	~37 %
IGCC	~45 %

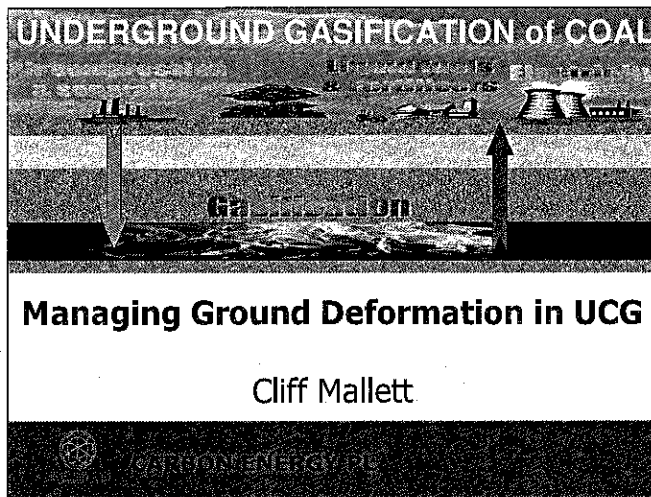
The efficiency of UCG with carbon dioxide removal is still better than many existing high emission coal fired plants.

**Conclusions**

- ❖ Underground coal gasification can provide an alternative source of fuel for power generation
- ❖ This fuel can be used efficiently in modern gas turbine plant, although some modifications must be made
- ❖ Carbon dioxide separation to reduce the Greenhouse emissions is feasible
- ❖ The cost of power can be competitive with conventional power generation



## Managing Ground Deformation in UCG



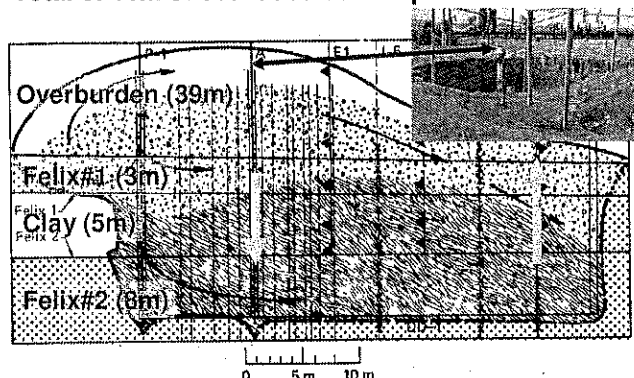
Ground deformation resulting from the removal of coal by gasification is the key source of environmental concerns, such as subsidence, and can lead to flow-on problems with groundwater. This presentation was prepared by Carbon Energy largely using material supplied by CSIRO.

### Why is Deformation an Issue?

- Commercial scale UCG removes similar coal volumes to a large longwall mine
- UCG Designs must provide consistent high volume gas production, and be viable with large scale extraction
- Cavity collapse results in induced permeability and subsidence
  - Changes gasification conditions with water inflow
  - Cause mixing in overlying aquifers
  - Surface impacts

### Hoe Creek #3 Trial (USA, 1979)

- Total of 11m of coal at 39-55m depth

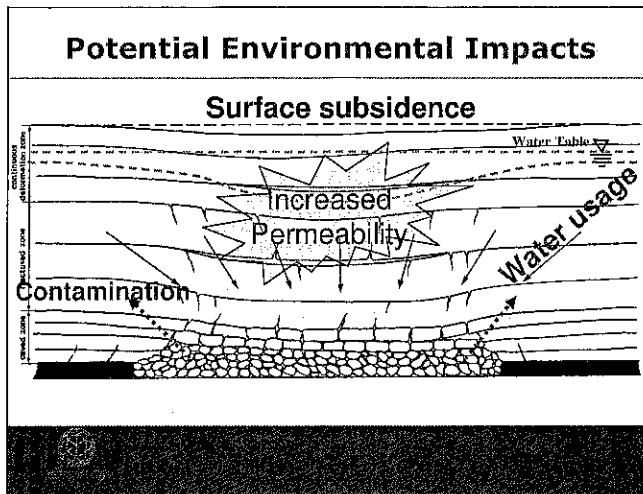


This shows the cavity generated during the Hoe Ck #3 trial, which had both subsidence and groundwater contamination issues.

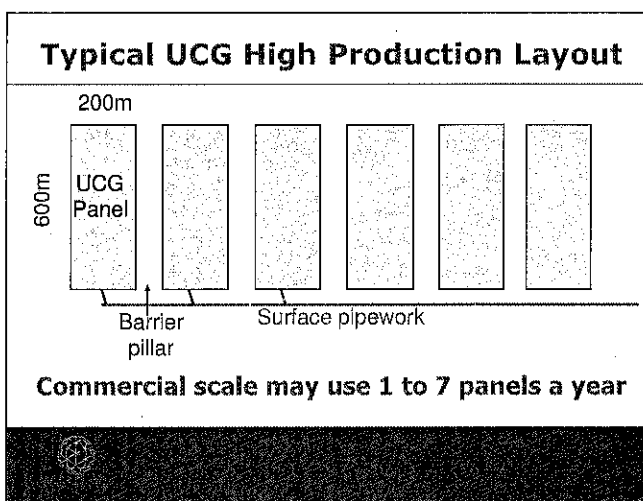
The objective was to gasify a section of the Felix#2 coal seam using single injection and production wells (indicated with arrows).

In reality, the overlying Felix#1 seam was also gasified with the resulting growth of a large cavity.

Given the shallow depth, the resultant subsidence opened.



The increase in permeability in the overburden can result in far greater water movement than would occur in strata that had not been deformed.



This block layout is similar to longwall panels in underground coal mining.

### What can be done about Deformation?

- Predict ground and water behaviour from site characterisation data
- Incorporate whole-of-life water flow into UCG operational designs
- Assess environmental impact models & monitor
  - Surface features
  - Groundwater systems

**But we cannot stop deformation, and if impacts cannot be managed, we must abandon the site for UCG**



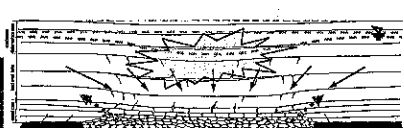
## Understanding Deformation

- UCG is analogous to longwall mining
  - Comparable coal will be removed
  - Thickness of coal – ash left but more coal taken
- Learn from longwall mine behaviour
  - We know that deformation is severe immediately above a cavity, but decreases in impact at higher levels
- Apply verified longwall predictive models to UCG eg COSFLOW
  - Stress and Strata movement
  - Fracture and Induced permeability
  - Fluid flow



## Critical Implications for UCG

- Large scale shallow UCG extraction will
  - Open direct pathways from surface to gasification cavity
  - Disrupt groundwater requirements for gasification
- Minimum depth for large scale extraction 300m
  - Maintain 150m of undeformed buffer over disrupted strata
  - At depth, in seam drill holes better than vertical holes
- Above 300m only partial extraction is safe
  - This limits UCG gas production levels achievable

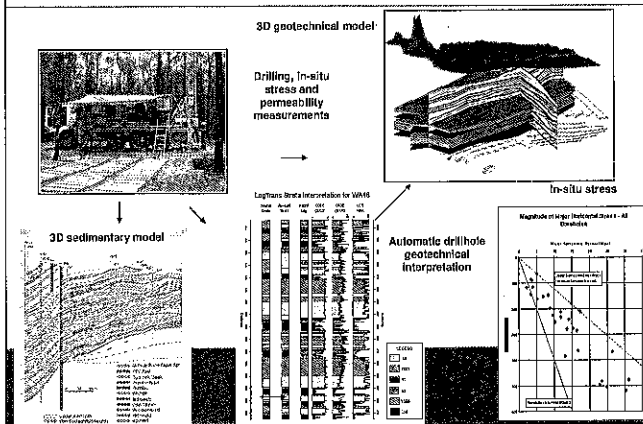


## Managing Deformation

- **Integrated site characterisation**
- **Numerical modelling**
  - Mine Water
  - Mine subsidence
- **Field monitoring**
- **Subsidence control**



## Site Characterisation

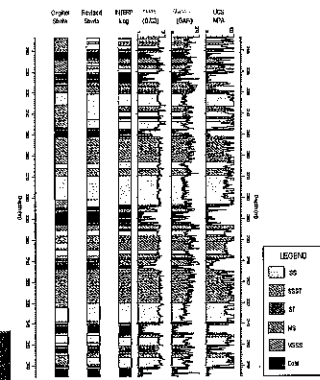


Interpretation of geological data is required to provide inputs to the models.

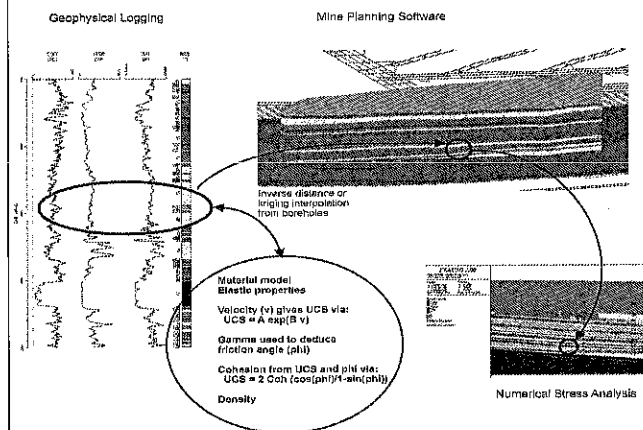
## Automated Log Transformation

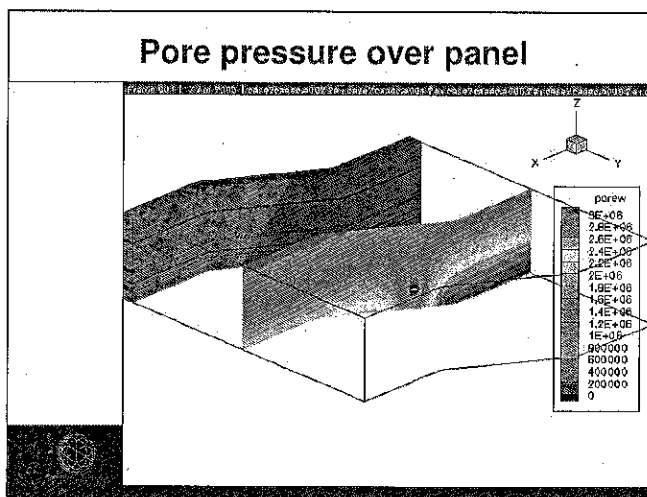
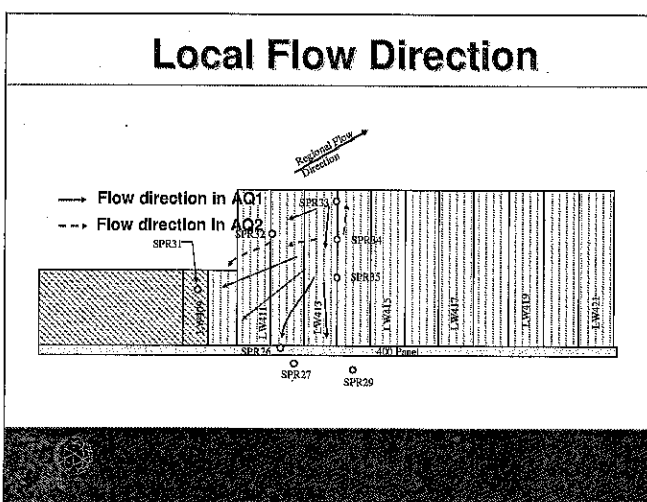
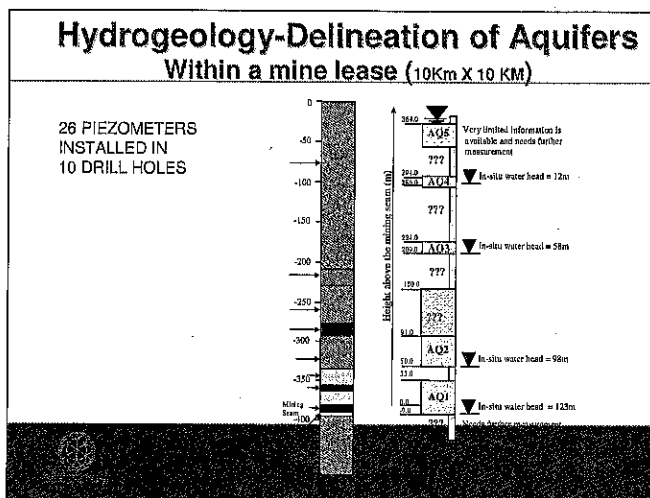
The computer program LogTrans is used to identify Coal, Mudstone, Siltstone and Sandstone from their unique petro-physical signatures using the density, natural gamma and sonic velocity geophysical logs.

The figure shows the geological interpretation of a control hole. The first column is the geological classification from the geologist. The second column is the geophysical conciliated geological classes for LogTrans' training processing. The third column is the LogTrans interpretation from the geophysical logs presented in the other columns.

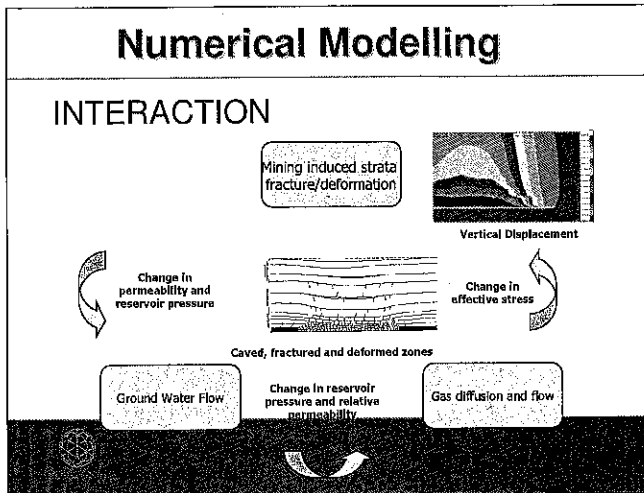


## From Borehole to Numerical Model





Modelling needs to be comprehensive to examine changes in properties of the overburden caused by deformation.



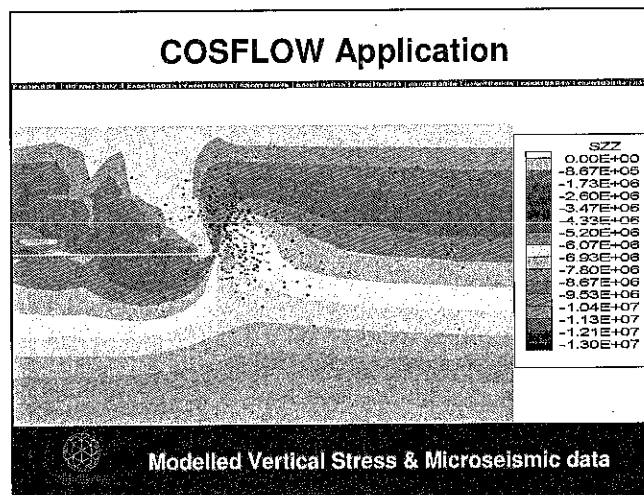
Fracture/deformation, groundwater flow and gas diffusion/flow are interrelated.

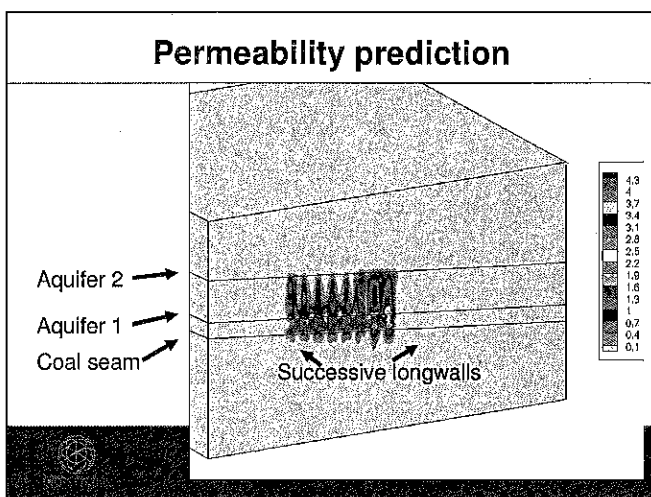
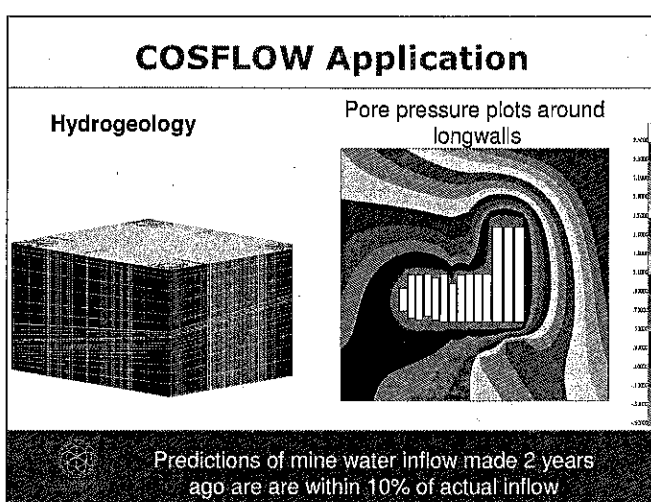
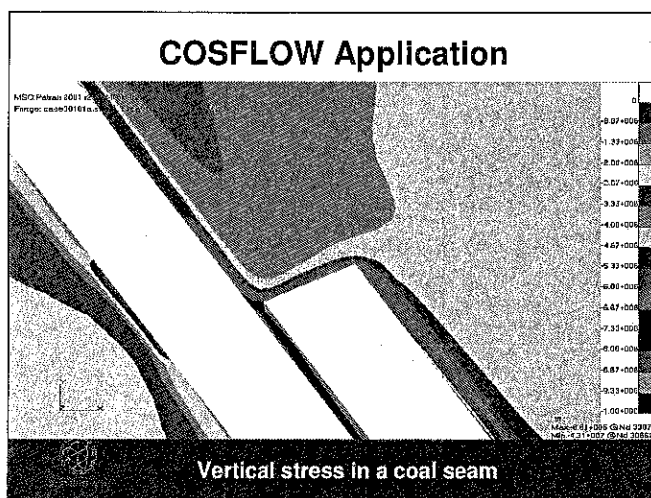
## COSFLOW

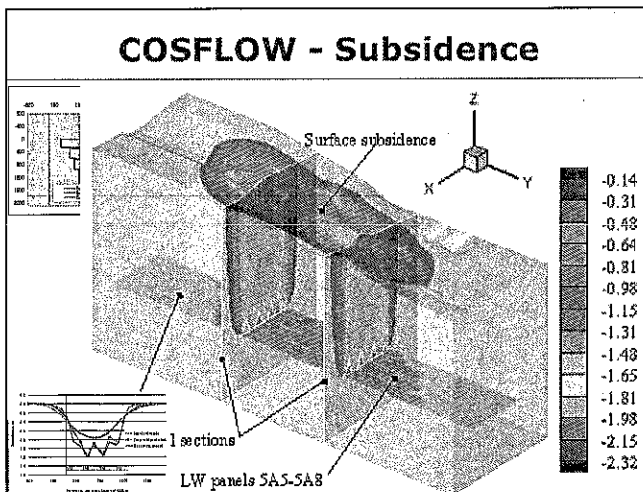
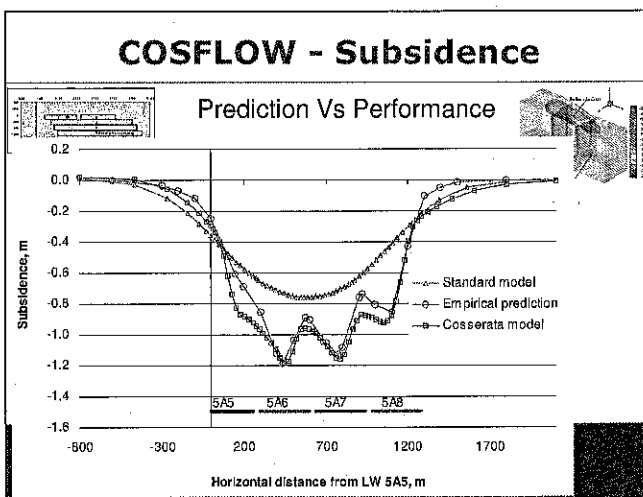
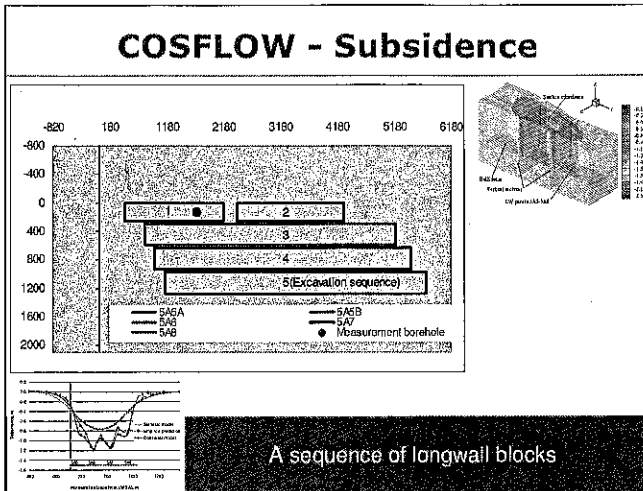
**COSFLOW is a coupled dual porosity two phase flow model developed with a specific objective of addressing the mine issues, such as ground deformation, water flow and gas emission**

- Couples rock mechanics of layered strata with one or two phase compressible fluid flow
- Cosserat Continuum => efficient simulation of the deformation behaviour of stratified rock
- Estimates rock fracture induced changes in hydraulic properties (e.g. permeability and porosity)
- Simulates water and gas flow through fractured rock

COSFLOW is a program developed  
By CSIRO and JCOAL & NEDO



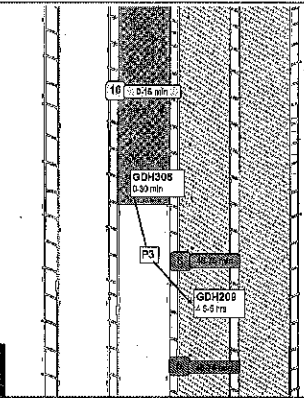




## Connectivity in Goafs

### Tracer gas studies(1)

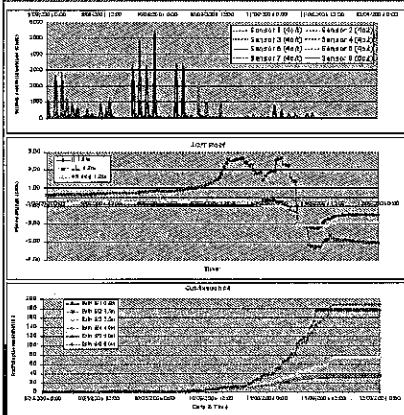
- Gas migration between adjacent longwall panels
- Longwall goaf – behaves as one system for gas
- Gas pressure and buoyancy effects – across all goafs



## Managing Deformation Impacts

- Predict ahead
  - Reject area for UCG if unsuitable
  - Manage the issues
- Management plan for risks
  - Monitor insitu – know what is happening and have a planned response for all identified risks
  - stop activity if it causes problems
- Active mitigation
  - Specific operational procedures
  - Innovative practices

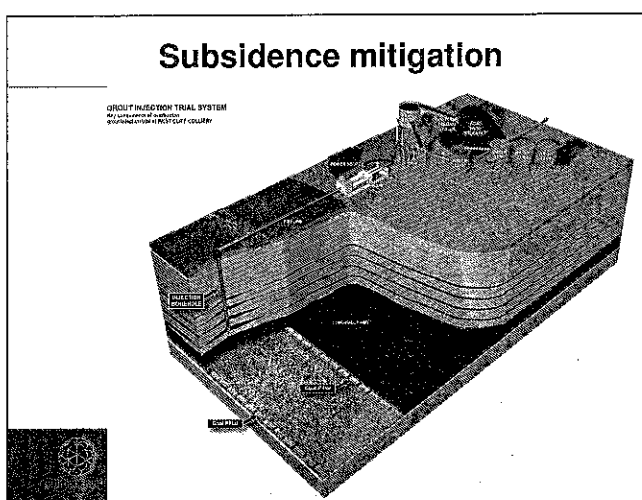
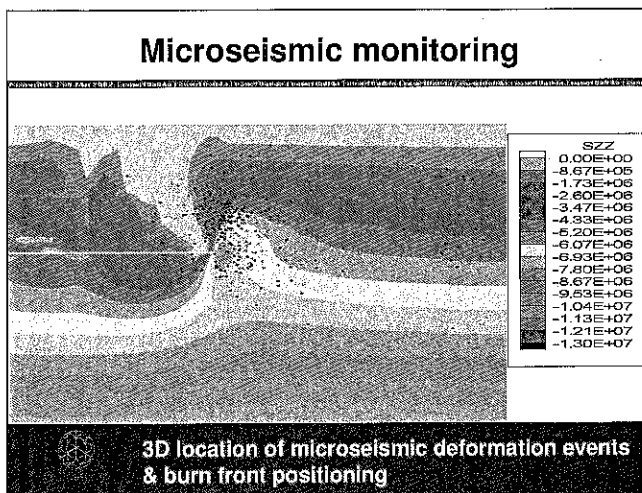
## Geotechnical monitoring



Microseismic monitoring

Stress monitoring

Displacement monitoring



Modelling allows for testing of the arrangement of gasifier modules to test low subsidence approaches.



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