

**REVIEW OF UNDERGROUND COAL
GASIFICATION TECHNOLOGICAL
ADVANCEMENTS**

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SUMMARY

Underground coal gasification (UCG) involves injecting steam and air or oxygen (O₂) into a coal seam from a surface well. The injected gases react with coal to form a combustible gas which is brought to the surface in a production well, cleaned and used as a fuel or chemical feedstock. A cavity is formed as the coal burns and the roof is allowed to collapse. This process results in lateral growth of the gasifier in the seam and is allowed to continue until the quality of the product gas declines. When this occurs the seam is re-ignited at a new location further along the gasifier. Once the coal within the underground gasifier has been exhausted, new injection and production wells are drilled alongside the exhausted gasifier and the process is repeated.

UCG has the potential to exploit coal resources which are either uneconomic to work by conventional underground coal extraction, or inaccessible due to depth, geology or other mining and safety considerations. The successful development of UCG will not only depend on advances in the use of technology but also on demonstrating that a clean energy can be produced without detriment to the environment. As a method of exploiting coal, UCG represents a substantial environmental improvement on the combination of coal mining and surface combustion of coal. A successful commercial application could significantly extend the coal energy reserves of the UK, both onshore and possibly also near-offshore.

Despite considerable research and testing world-wide, no commercially viable project has yet been demonstrated to western standards. Research has been conducted principally in Western Europe, USA, China, the former Soviet Union and Australia. Large-scale, shallow seam-based schemes have operated in the Soviet Union for more than 40 years and new shallow seam technologies are now being demonstrated in China where UCG is considered as a potentially important clean coal technology.

Most research into UCG has concentrated on coals at relatively shallow depth. Recent work, particularly in Europe where there are substantial coal resources at depth, has focused on the exploitation of UCG in deep coals accessed using advanced guided drilling techniques. Field trials at Thulin in Belgium (1979-1987) and subsequently at 'El Tremadal' in Spain (1993-1998) demonstrated the technical feasibility of UCG at depth. These trials involved the drilling and linking of two wells, an injection well to feed the reactant gases to the gasifier, and a production well to carry the product gases to the surface for processing and use.

An integrated 50MW_e UCG-power generation scheme could be commercially feasible, but smaller schemes are likely to be marginal in present market conditions. However, technical uncertainties remain which need to be addressed in field trials.

Interaction of the underground reactor with the surrounding strata needs to be better understood to facilitate selection of appropriate sites, and target seams, and to ensure the gasification process can be controlled to prevent the escape of pollutants. Hydro-geological information will be particularly important in this respect.

The guided drilling technology currently available is suitable for the envisaged deep UCG applications, but its accuracy, reliability, repeatability and cost has yet to be established in practice.

Critical assumptions about gasifier growth also need to be confirmed to ensure that sufficient coal can be accessed from a drilled gasifier circuit to justify commercial investment in the technology.

CONTENTS

Page No.

1	INTRODUCTION	2
1.1	Benefits of UCG	2
1.2	Commercial Factors	3
2.	UCG PROCESSES	4
2.1	Introduction	4
2.2	Gasifier Performance	4
2.3	Gasification Circuit	6
2.4	Cavity Behaviour	6
2.5	Gasifier Growth	7
2.6	Cavity Growth Modelling	7
2.7	Production Flow Limits	9
2.8	Treatment Of UCG Product Gas	9
3.	REVIEW AND ANALYSIS OF THE UGE TRIAL	10
3.1	Introduction	10
3.2	Site Selection	10
3.3	Site Geology	11
3.4	The Gasifier Circuit	11
3.5	Injection Wells	11
3.6	The Production Well	12
3.7	The Injection System	12
3.8	Ignition of the Gasifier	13
3.9	Treatment Of The Product Gas	13
3.10	Monitoring and Control	14
3.11	Technical Problems Encountered During the UGE Operation	15
3.12	Key Results of the UGE Trial	17
3.13	Shortcomings of the UGE Trial	17
4.	GUIDED DRILLING TECHNOLOGIES	18
4.1	Introduction	18
4.2	Guided Drilling Technologies	19
4.3	Measurement and Guidance Technology	20
4.4	Borehole Stability	20
4.5	Borehole Design	21
4.6	Drilling Contracts	21
4.7	Application of Oil and Gas Industry Guided Drilling Technology	21
4.8	Application of Coal Industry Guided Drilling Technology	22
4.9	Relevance to UCG Development in the UK	23
5.	ENVIRONMENTAL IMPACT AND ITS CONTROL	23
5.1	Introduction	23
5.2	Surface Impacts	24
5.3	Subsurface Impacts	26
5.4	Monitoring and Control of Environmental Impacts	27
5.5	Hydro-geology	28
5.6	Key Environmental Issues	29

6.	COMMERCIAL FEASIBILITY	29
6.1	Introduction	29
6.2	A Cost Model	30
6.3	Project Scale for Commercialisation	32
6.4	Commercial Interest	32
7.	WORLDWIDE REVIEW OF UCG DEVELOPMENTS	32
7.1	Introduction	32
7.2	Australia	33
7.3	China	33
7.4	Japan	34
7.5	New Zealand	34
7.6	Russian Federation	35
7.7	USA	36
7.8	Former Yugoslavia	37
7.9	Other Countries	37
8.	POTENTIAL GEOLOGICAL RESOURCE FOR UCG IN THE UK	37
8.1	Introduction	37
8.2	Onshore Area	37
8.3	Offshore Area	37
8.4	General UCG Prospects in the UK	39
9.	REGULATION OF UCG ACTIVITIES IN THE UK	40
9.1	Introduction	40
9.2	Coal Ownership	40
9.3	Health and Safety	40
9.4	Environmental Regulations	41
9.5	Gas Storage Standards	41
10.	RECOMMENDATIONS ON FUTURE R&D	42
10.1	Introduction	42
10.2	A Drilling Trial	43
10.3	UCG Field Trial	44
10.4	Drilling Issues	46
10.5	Fundamental and Other Research	47
11.	CONCLUSIONS	47
12.	ACKNOWLEDGEMENTS	49
13.	REFERENCES	49

TABLES 1-6

FIGURES 1-7

APPENDIX 1: SURFACE COAL GASIFICATION

APPENDIX 2: SUMMARY OF UCG TRIALS IN THE USA

APPENDIX 3: OIL AND GAS INDUSTRY GUIDED DRILLING TECHNOLOGY SERVICES

APPENDIX 4: ENVIRONMENTAL STUDIES AT EXPERIMENTAL UCG SITES
IN THE USA

APPENDIX 5: HYDROLOGY OF UK COALFIELD AREAS

APPENDIX 6: POROSITY AND PERMEABILITY DATA FOR UK
CARBONIFEROUS

APPENDIX 7: SUMMARY OF COAL-BEARING AREAS IN THE UK

APPENDIX 8: A PRELIMINARY REVIEW OF UK OFFSHORE COAL
FORMATIONS

REVIEW OF UNDERGROUND COAL GASIFICATION TECHNOLOGICAL ADVANCEMENTS

FOREWORD

The principal aim of the study was to review and assess recent developments in underground coal gasification (UCG) technologies, particularly in relation to initiation of the UCG process, monitoring, control and cavity growth in deep coal seams.

The study was undertaken by Wardell Armstrong with the assistance of the British Geological Survey (BGS) and contributions from the University of Nottingham. The project was supervised by Mrs Heather Tilley of ETSU on behalf of the UK Department of Trade and Industry, Cleaner Coal Technology Transfer Programme. The contract was initiated on 26 October 2000 and the work completed in July 2001.

The scope of the review encompassed the following topics:

- Literature search and Internet survey concentrating on post 1989 UCG knowledge, deep guided drilling, ignition and combustion control, cavity growth and stability, process sustainability, gas conditioning, downstream gas use, process costs, environmental protection, realisation of environmental benefits and commercial interest
- A world-wide review of UCG related technology and current R&D
- Critical review of recent European research and trial results
- Study of environmental aspects (technical and regulatory)
- External consultations, discussions and meetings
- A financial appraisal of UCG and the likely impact of new and emerging technologies on commercial feasibility and the market
- Determination of future R&D needs for the UK

External Consultations

Contact was made with various organisations, companies, research institutes and individuals both in the UK and overseas. These consultations helped to establish the expectations of the market for UCG, provide a current worldwide and UK perspective, and identify relevant research activities.

Manufacturers and service companies were approached to elicit details of recent developments in geophysical exploration techniques, guided drilling and down-hole ignition systems.

1 INTRODUCTION

UCG is the process by which coal is converted *in situ* into a combustible gas that can be used as a fuel or chemical feedstock. Knowledge of the process of gasification of coal has existed for many years. Despite considerable research and testing, no commercially viable project has yet been demonstrated to western standards. Research has been conducted principally in Western Europe, USA, China, the former Soviet Union and Australia. Large-scale, shallow seam-based schemes have operated in the Soviet Union for more than 40 years. New shallow seam technologies are being developed in China where UCG is considered as a potentially important clean coal technology ready for commercial exploitation in the short-term.

Early research into UCG concentrated on coals at relatively shallow depth. These projects mainly involved the use of existing and purpose made mine entries and underground infrastructure, shallow boreholes or a combination of the two approaches (Thompson et al, 1976). More recent work in the USA and Europe has concentrated on the exploitation of UCG in coals accessed using advanced drilling techniques. Within Europe, substantial resources of unmined coal at depth represent the target for UCG exploitation. Field trials at Thulin in Belgium (1979-1987) and subsequently at 'El Tremedal' in Spain (1993-1998) have demonstrated the technical feasibility of UCG at depth.

The El Tremedal project was the first trial in a comprehensive seven year, 40 million ECU, field and laboratory R&D programme suggested by the European Working Group on UCG after a detailed review of previous work on the topic (EWG, 1989). Two field trials were recommended, one at around 600m in coals mainly representative of southern Europe and the second at around 900m to confirm the feasibility of UCG in bituminous coals typical of major coal resources in mid and northern Europe. The idea was to maximise data acquisition and experience in the first trial to provide a sound basis for tackling the more challenging engineering and geological conditions in the second trial.

The El Tremedal project demonstrated some key technologies, highlighted areas requiring further research and provided information on the likely environmental impacts of the process. Analysis of this trial provides a basis against which recent developments in technologies relevant to UCG can be objectively assessed. Thus, recommendations can be made as to current R&D needs and the aims of a future trial to move the development of UCG towards commercialisation.

1.1 Benefits of UCG

As a gas producer a UCG scheme would compare favourably with a town gas plant. These had a history of poor environmental performance during operation and left a legacy of polluted ground that has proved costly to remedy.

As a method of exploiting coal, UCG represents an environmental improvement on the combination of coal mining and surface combustion of coal. It is also safer and intuitively more efficient.

Environmental benefits of UCG over underground coal mining for fuelling power generation include:

- Lower fugitive dust, noise and visual impact on the surface
- Lower water consumption
- Low risk of surface water pollution
- Reduced methane emissions
- No dirt handling and disposal at mine sites
- No coal washing and fines disposal at mine sites
- No ash handling and disposal at power station sites
- No coal stocking and transport
- Smaller surface footprints at power stations
- No minewater recovery and significant surface hazard liabilities on abandonment.

Additional benefits are:

- Health and safety
- Potentially lower overall capital and operating costs
- Flexibility of access to mineral
- Larger coal resource exploitable

At present, natural gas offers attractions as a clean fuel that UCG may find difficult to compete with other than if it has a compelling cost advantage. However, natural gas reserves have a finite life. At some time it may prove economically and strategically beneficial to replace, or complement, natural gas power generation with UCG schemes.

The carbon dioxide (CO₂) emissions from the 'best' recent UCG trials are compared with emissions from conventional fossil fuel power stations in Table 1. The emissions attributable to coal exclude consideration of any CO₂ emitted when mined (methane (CH₄) is 21 times more potent than CO₂ as a greenhouse gas). Assuming an average methane emission of 15m³ t⁻¹ of UK coal mined, approximately 0.005 tons of CO₂ equivalent is attributable to coal mine emissions per MWh of electricity generated using indigenous coal.

1.2 Commercial Factors

Aspects relevant to an assessment of the commercial viability of the developing technology and hence the needs of future R&D include:

- geological variables and relationship to drilling difficulty and cost
- power output and life of the gasifier
- subsidence effects
- safety of production operations
- commercial perspective of UK industry

- strategic value of UCG to the UK
- environmental sensitivities
- the potential market – chemical and power generation industries.

2. UCG PROCESSES

2.1 Introduction

UCG involves injecting steam and air or O₂ into a coal seam from a surface well. The injected gases react with coal to form a combustible gas which is brought to the surface in a production well, cleaned and used as a fuel or chemical feedstock. A cavity is formed as the coal burns and the roof collapses. This results in lateral growth and is allowed to continue until the product gas quality deteriorates. The greater the lateral growth, the longer the life of a gasifier and the more cost-effective the operation. When the quality of the product gas falls, fresh coal is ignited further along the injection well. Once the coal within the underground gasifier has been exhausted, new injection and production wells are drilled and the process is repeated.

Gasification differs from combustion which takes place when coal is burned in excess O₂ to produce CO₂ and water. Another important difference between coal combustion and coal gasification is in pollutant formation (Moreea-Taha, 2000). The reducing atmosphere in gasification converts sulphur (S) from coal to hydrogen sulphide (H₂S) and nitrogen (N) to ammonia (NH₃), whereas combustion (oxidation) produces sulphur dioxide (SO₂) and oxides of nitrogen (NO_x).

Underground gasification cannot be controlled to the same extent as a surface process as the coal feed cannot be processed. Knowledge gained on surface gasifiers can therefore be invaluable to researchers and operators of UCG processes. Research on surface gasifiers shows that low rank coals tend to be more reactive than bituminous coals and that mineral matter may have an important catalytic effect on gasification rates. Further details are provided in Appendix 1.

The principal processes can be divided into two stages, namely pyrolysis (also known as carbonisation, devolatilisation or thermal decomposition) and gasification. The chemical complexities are illustrated in Figure 1 (adapted from Donne et al, 1998). During pyrolysis coal is converted to a char releasing tars, oils, low molecular hydrocarbons and other gases. Gasification occurs when water, O₂, CO₂ and H₂ react with the char.

The main gases produced are CO₂, CH₄, H₂ and carbon monoxide (CO). O₂. CH₄ is essentially a product of pyrolysis, rather than gasification. Its formation is favoured by low temperature and high pressure.

2.2 Gasifier Performance

Before examining the results of the Underground Gasification Europe (UGE) trial it is helpful to understand the basic geo-technical and thermodynamic processes, and the benefits of increasing depth on gasification performance.

In a theoretical appraisal of the gasification process, Chappell (1998) defined the autothermal chemical equilibrium (ACE). This is a condition at which the heat value of the product gas and the conversion efficiency of the gasified coal (chemical energy of product gas/chemical energy of gasified coal) is a maximum.

At high temperatures and pressures (say 5MPa, 900°C), ACE conditions are approached rapidly but at lower temperatures and pressures the time to attain equilibrium greatly exceed the residence time of the gases in the gasifier and therefore ACE will not be attained. Product heat value and conversion efficiency at ACE increase as temperature and pressure are reduced but necessary contact times for reaction increase rapidly beyond practical limits.

The ACE temperature falls as the molar ratio of steam to O₂ is increased. At the same time, the dry product heat value increases due to increased methane synthesis. Uncontrolled groundwater flows into the gasifier at El Tremedal increased the steam to O₂ ratio, suppressing the ACE temperature. Optimum gasification conditions could therefore not be attained due to the impracticably long contact times between gas and char necessary to achieve equilibrium. Nevertheless, gas with a satisfactory heat value of 10.9MJ m⁻³ (dry basis, lower heating value) was obtained.

Although complex in reality, the basic reactions can be generalised to a simple empirical form:

- $C + O_2 \rightarrow CO_2$ (+heat)
- $C + CO_2$ (+heat) \leftrightarrow 2CO
- $C + H_2O$ (+heat) \leftrightarrow H₂ + CO
- $C + 2H_2 \leftrightarrow CH_4$ (+heat)

Carbon oxidation reactions dominate at low temperature and pressure leading to a high CO₂ content in the product gases and a low heat value. Such conditions are typical of early shallow UCG experiments.

During pyrolysis coal, subjected to high temperatures, yields higher heat value gases than ACE gasification products for a relatively small consumption of O₂.

Pressure increases the proportion of coal pyrolysed to form methane thus raising the heat value of the product gases. There is also some evidence to suggest that elevated pressures cause pyrolysis processes to penetrate *in situ* coal, further enhancing the gasifier yield.

Optimisation of reaction conditions might at best produce gas with a heat value of 16MJ m⁻³. The fact that gas of almost 11MJ m⁻³ was produced at El Tremedal in non-ideal conditions suggests that the UCG process is relatively insensitive. At higher temperatures (and pressures) than those achieved in Spain, methane produced by pyrolysis could boost the calorific value of the product gas and ACE conditions may not be important.

2.3 Gasification Circuit

The gasification circuit requires a flow link to be achieved between an injection and a production well. Methods of achieving the link are:

- Accurate drilling assisted by a target device in the vertical well if necessary.
- Reverse combustion, involving ignition at the base of the production well.

A reverse combustion facility was installed at El Tremedal, but was not needed and may not have worked. Other than in low rank, shrinking coals, it is unlikely that reverse combustion is a reliable option. Reverse combustion and hydrofracking were unsuccessful in trials in France (1981, 1985, 1986). Reverse combustion was also unsuccessful at Thulin in Belgium. Modern guided drilling technology should be capable of achieving the required well connections.

2.4 Cavity Behaviour

Installation of well pairs (injection and production wells) is costly and therefore it is desirable to gasify the maximum volume of coal between a well pair. As gasification proceeds, a cavity is formed which will extend until the roof collapses. This roof collapse is important as it aids the lateral growth of the gasifier. Where the roof is strong and fails to break, or where the broken ground is blocky and poorly consolidated, some fluid reactants will by-pass the coal and the reactor efficiency could decline rapidly. This is a known problem in shallow gasifiers (eg Hoe Creek I and II, USA).

The occurrence of significant by-pass may be manifested by the presence of O₂ in the product gas or a rise in product temperature due to the combustion of product gas with by-pass O₂. This would mark the end of the reactor life.

This situation is most likely to occur in shallow coals and hence poor product gas quality would be anticipated. However, at depths of say 500m or greater, high *in situ* stresses in weak UK Coal Measure strata should ensure compaction after caving to reduce the risk of bypass occurring. Seams with strong sandstone roof sequences, such as the Parkgate seam in parts of the Yorkshire coalfield, may not necessarily be suitable for UCG. Water seepage through fractured well-developed sandstones could also be a problem. However, most seams in the UK have relatively weak roof strata.

Mass balance results from the El Tremedal experiment indicated a cavity width of five times the seam thickness. However, this evidence of lateral growth is of limited value due to the small gasifier volume, the short duration of gasification and because it is unlikely any significant caving and compaction occurred. Conservative assumptions as to gasifier width to length ratios have therefore to be made in any financial models pending experimental verification.

In general, as depth increases, conditions should become increasingly favourable to gasifier development with a lower risk of bypass problems occurring, except possibly in strong roof conditions.

2.5 **Gasifier growth**

Theoretically, with good caving of the roof and rapid compaction to a very low permeability, a high aspect ratio (gasifier width/channel length) could be achievable but the practical limit is very uncertain. The EWG report states *to what width a reactor will develop under high overburden pressures in this coal seams cannot definitely be assured with today's knowledge* and requires testing in a prolonged trial. Aspect ratios of 0.06 to 0.1 were used in the EWG report. Modelling and simulations of cavity growth have been undertaken but without verification by comparison with field trial results the predictions must be treated with caution and the uncertainty remains.

In practical terms, it is coal volume available for gasification per borehole pair (assuming a simple linear gasifier) that determines the life of a gasifier for any given output. Reduction in gasifier width can be compensated for by choosing a thicker coal seam or by increasing injection well length at the design stage. There could be a lag between roof caving, consolidation and transmission of reactants to new coal areas in a developing gasifier. Gas quality could therefore fluctuate at any particular ignition location and care would be needed not to move the ignition point prematurely.

A technique known as 'filtration' relying on permeability enhancement caused by pyrolysis has been suggested as a possible means of providing a connection to an offset well that could be used to extend the width of the gasifier. There is a belief that at intermediate and greater depths, coal permeability will be too low for effective filtration to be attained. Other techniques may therefore need to be examined and developed to maximise cost effectiveness of the installation and energy recovery. These are likely to involve more complex drilling configurations than the simple linear gasifier used in field trials.

Gasifier Control

The most successful gasifier or reactor control process, developed in the USA, involves the use of a burner attached to coiled tubing. The device is used to burn through the borehole casing and ignite the coal. The ignition system can be moved to any desired location in the injection well. This 'controlled retraction of ignition point' (CRIP) technique enables a new reactor to be started at any chosen upstream location after a declining reactor has been abandoned. The CRIP technique has been used at shallow depth in the Rocky Mountain 1 trial (USA) and at intermediate depth in the UGE trial, Spain. CRIP provides a satisfactory means of controlling the underground process to maintain gas quality.

2.6 **Cavity Growth Modelling**

Various mathematical models have been developed to evaluate the likely growth of an underground gasifier. An original approach was developed by Wilks (1983) at British Coal's Mining Research and Development Establishment. Wilks examined the results of USA trials. He concluded that a pear-shaped cavity would grow around the injection well, narrowing towards the production well (Figure 2). The model assumed that combustion and gasification reactions are uniformly distributed over the whole height of the reactor and that the roof caves immediately into the cavity formed by gasification and subsequently compacts. The assumption of caving is consistent with the

observations of Gunn and Krantz (1987) who reported on the spalling of cavity roof rocks due to the thermomechanical stresses generated during drying.

The effect of thermal stress on rocks can be evaluated in the laboratory (Camp et al, 1980) by heating rock cores to 1000deg C in an inert atmosphere and counting the distance between successive bedding fractures on photographs. No detailed tests of this type have been reported for UK Coal Measure rocks.

Coeme et al (1993) incorporated a representation of the chemical processes into the Wilks concept. Subsequently, researchers have replaced the radial flow simplification used by Wilks with equations representing two-dimensional fluid flow in porous media (Mathy et al, 1994) and a Boundary Element Method to obtain solutions. The main parameter of this improved model is the ratio between the permeability of the high and low permeability zones (see Figure 2). Interpretation of this work leads to two important conclusions:

- gasification growth leads to a less uniform distribution of flow in the system that could explain the observed decrease of gasification efficiency with growth;
- an increase in separation between injection and recovery wells during cavity growth (assisted by CRIP) could increase the duration of reactant-coal contact and hence improve gasifier performance.

As the permeability ratio between the caved zone and the peripheral gasification zone increases, the life of the gasifier, the volume of coal gasified and the power output increase. The end of the gasifier life is considered to occur when the low permeability zone arrives at the production well.

The likely behaviour of a growing cavity has been modelled with varying degrees of complexity, generally based on the original concepts of Wilks (1983). During his deliberations, Wilks considered additional detail which could not be easily mathematically represented, in particular, the possibility of irregular cavity growth resulting in the isolation of patches of coal from contact with reactants reducing the efficiency of the gasifier (Wilks, personal communication, 1983).

There is scope for further modelling. Geotechnical aspects in respect of caving and permeability of caved material could be developed using modelling concepts established from longwall mining research. Computational fluid dynamics (CFD) could also be useful for improving the understanding of the likely flow and combination processes. However, without any test results, none of the models can be calibrated or validated.

A two-dimensional (2-D) cavity growth model has been developed in Belgium by IDGS and the University of Liege, and a three-dimensional (3-D) model at TU DELFT in the Netherlands. The intention was to apply these models to the El Tremedal trial to presumably verify them as well as to assist in the interpretation of the results. Too little gasification was done for these models to be made full use of. However, any future trial should include for the development and verification of a cavity growth model applicable to deep seams.

The cavity shape described by numerical models generally assumes a fixed injection point. CRIP allows this location to be moved thus extending the cavity envelope.

2.7 Production Flow Limits

The energy output of a UCG system depends on the flow rate of gaseous products and the heat value of the gas mixture. The volume flow of the product gas is typically four times the injection flow so the limiting factor is the dynamic resistance of the production well. The mass flow capability of a well is proportional to input pressure. Increasing well depth increases the product gas density and pressure. The mass flow gain due to pressure increase exceeds the frictional loss due to increased borehole length. Increasing the diameter of production tubing also raises the limiting flow rate.

2.8 Treatment of UCG Product Gas

The gas treatment system must accept product gas at elevated temperatures and high pressures (5.3MPa at El Tremedal) from the production wellhead, clean and dry this stream and route it to the end use while maximising the potential for energy conversion.

When the product gas reaches the surface it contains energy not only in its chemical composition but also in its high temperature, pressure and velocity. In the Spanish trial the volume flow rate of the product gas stream was typically about four times greater than that of the injection gas stream.

Product gas would have to be cleaned prior to utilisation to remove NH_3 and H_2S derived respectively from S and organic N_2 in the coal respectively. This could be achieved using proven, commercially available, high-pressure separation techniques.

Deep UCG will produce a fuel gas consisting of a mixture of CO_2 , CO, H_2 , CH_4 and water, together with pollutants such as H_2S , HCN, NH_3 and traces of other gases. There will also be particulate matter entrained in the gas flow.

The product gases must be processed to ensure environmental legislation can be met, and to condition the gas to satisfy the end-user. The end-user will specify the range of gas compositions, heat values, moisture content and condition. The most likely destination of the gas is a gas turbine for power generation. Concerns by the end-user will be gas quality, variability and corrosive nature.

The gas exhausted by the end-user will contain some atmospheric pollutants, the emissions of which will be regulated. Through engine design and treatment of the fuel gas, these emissions can be minimised.

Hot gas cleaning techniques have been developed to meet the needs of power generators to clean fuel gas before use, or flue gas after combustion (DTI, 1996). These cleaning processes are capable of removing a diverse range of contaminants from hot gases. In addition to protecting the environment, use of cleaned gas can result in benefits to equipment performance and reliability.

The raw product gas from UCG is similar to that produced by surface gasifiers for which gas cleaning technologies have already been developed.

The US Department of Energy has co-sponsored research with manufacturers in the development of gas turbines for use with dirty gases such as UCG products (Davis et al, 1997). Gas turbine research has also taken place in the UK in conjunction with surface gasifier development. Currently, Alstom and Cranfield University are involved with a UK-China technology transfer project, sponsored by the DTI and managed by Wardell Armstrong, which is investigating the application of gas turbine technology to shallow UCG projects in China.

3. REVIEW AND ANALYSIS OF THE UGE TRIAL

3.1 Introduction

The UCG trial at El Tremedal in Spain, undertaken by UGE, represents the current state-of-the-art in high pressure, deep seam in situ gasification. The trial was initiated in 1989 and the site finally abandoned in 1998. The information reviewed comes from published papers and reports (DTI, 1999; ETSU, undated; Green, 1999; UGE 1999).

UGE was a research consortium funded by government organisations in Spain, Belgium and the UK and also supported by the European Commission under the THERMIE Program for the development of innovative energy technologies. The aim of the UGE project was to demonstrate the technical feasibility of performing UCG at intermediate depths, between 500m and 700m.

The field trial involved:

1. Site selection
2. Geological exploration
3. Installation of injection and production wells
4. Construction of surface plant for gas storage, injection, treatment and flaring and also water treatment
5. Process monitoring and control
6. Post burn investigations
7. Well sealing and site reinstatement

An outline chronology of the UGE trial is shown in Table 2.

3.2 Site Selection

The site was selected in general accordance with the criteria proposed by the EWG. It was recognised that a single trial could not be representative of all European coals and was intended to be the first of two trials. In retrospect it proved to be far from ideal especially in respect of the hydrogeology.

The coal rank was much lower than most of the deep coals that the technology would normally be applicable to in western Europe but it was of a coal type of which most UCG experience had been gained elsewhere, albeit at shallow depth. The site was

distant from any underground mining operations and had the approval of the Spanish authorities.

3.3 Site Geology

The geology of the site was investigated using three exploration boreholes. The target coal seam was 2m to 5m thick, dipping at 30° at a depth of 530-580m. Some 7-14m below lay another coal seam. The coal was of sub-bituminous rank, almost lignite. Proximate analysis yielded (by weight); 22.2% total moisture, 27.5% volatile matter, 36% fixed carbon, 14.3% ash and 7.6% S. The gross heat value (higher heating value) of the coal was 18.1MJ kg⁻¹ (28.5MJ kg⁻¹ dry, ash free).

A clayey sand layer above allowed water to migrate into the seam. Subsequently, it allowed some 17% of the produced gas to escape into the strata. Such a figure may be expected at shallow depth but may be considered excessive from a deep reactor. Low permeability limestone strata lay beneath the seams.

3.4 The Gasifier Circuit

The gasifier circuit is achieved by drilling and linking an injection well and a production well. The UGE trial used oilfield deviated drilling technology to position the ends of two boreholes, an injection well and a production well, within a metre of each other in a coal seam at depth. The wellheads of the two boreholes were 150m apart. The in-seam section of the injection well constituted the underground reactor or gasifier.

The complex installations of concentric tubing, cabling, piping and instrumentation required development of special procedures.

A perfect drilling intersection between injection and production well is not necessary. Provided the ends of the holes are sufficiently close a connection can be achieved using high-pressure N. If the N 'fracking' is unsuccessful there are two other options available to complete the linking, high-pressure water or reverse combustion initiated from the production well. As the production well was drilled to within 1m of the injection well at El Tremedal a link was easily established.

3.5 Injection Wells

The injection well (Figure 3) is the key component of a UCG system. Its position in the seam must be accurately known and adjustable so that the subsequent CRIP manoeuvres will consistently place the ignition point within the seam. This technique enables a new reactor site to be initiated when the quality of the gas at the existing reactor location deteriorates.

An injection well, was drilled with an initial near vertical section and then deviated to intercept and follow the upper coal seam of the succession for about 100m.

The role of an injection well is to introduce gasification agents, water and O₂, to the target coal seam. It also allows the introduction of an ignition device attached to coiled

tubing. This device is used to burn through the borehole liner and initiate the gasification process. The products of gasification flow to the production well.

In addition to an injection well and a production well, the UGE trial also involved a third well, a transverse injection well, intended for use in filtration gasification tests, which were abandoned when the experiment was prematurely terminated due to an explosion. This occurred when an accumulation of methane was inadvertently ignited (further details are provided in Section 3.11). There is some doubt as to whether the natural permeability of the coal at depth would have been sufficiently high for the filtration process to be effective in any event.

The well head was designed to accept surface pipe-work for the various feed gases as well as process monitoring cables which were required to reach the ignition point.

The deep UCG process is reliant on the use of directional drilling techniques but those employed at El Tremedal were not sufficiently refined. The drilling of the injection well was not sufficiently accurate to maintain it in-seam. The difficulty arose because the measurement-while-drilling (MED) sensors were located 12-14m behind the drilling bit. There were also problems with the lack of experience of the drolleries and contractual arrangements.

3.6 The Production Well

The production well (Figure 4) was an S-shaped (originally designed as vertical but the interception point with the injection well was relocated), cased borehole containing production tubing for high and low flow, capable of resisting the high temperatures, erosive and corrosive effects of the product stream. All components within the production system which came into contact with the product stream were fabricated from a high Nickel–Chromium–Molybdenum (Ni-Cr-Mo) alloy to accommodate the high S in the hot product gas. The production well was also equipped with a water-cooling capability, in order to control the well base temperature.

3.7 The Injection System

A UCG injection plant would normally consist of an air separation unit with associated cryogenic gas storage, high-pressure pumps dedicated to each input agent and associated safety features including monitoring and safety valves. At El Tremedal, liquified gases were brought onto site.

The crucial aspect of the injection system is that of gasification control. The variables at the injection manifold are the injection stream's composition, flow rate and pressure. UCG requires a facility to inject pressurised, controlled mixtures of O₂, N and water.

Analysis of tracer gas concentrations at the production well facilitated mass balance calculations, measurement of cavity growth, estimation of the tonnage of coal affected, gas losses to strata and gasification efficiency. Argon, present as an impurity within the injected gases was used as a tracer at El Tremedal. A facility to inject deuterium and helium tracers into the process flow was also included.

O₂ is required to promote exothermic reactions within the gasifier but need not be of high purity. Although costly to supply its use is optimised at the elevated pressures and temperature conditions of deep UCG. Increasing O₂ input raises the power output. Consumption of O₂ depends on pressure and temperature conditions in the gasifier. The O₂ consumption at El Tremedal was 0.3t per ton of coal affected.

N was available to purge the wells between gasification operations.

Water is required by the gasification process and is mixed with the O₂ at surface, with the help of a foaming agent. Water is also needed for cooling the production well and produced gas and also for flooding the gasifier after exhaustion.

3.8 Ignition of the Gasifier

Ignition of the gasifier was started 4m from the end of the production well by introducing a pyrophoric compound, tri-ethyl borane, to ignite a methane burner located at the end of the coiled tubing. Once the liner was burnt through, gasification agents were introduced.

The product gas was generated as the coal surrounding the ignition point was gasified, creating a caved zone which post-burn investigations indicated extended to at least five times the seam thickness. The dry product gas generated at El Tremedal consisted of roughly 40% CO₂, 12% CO, 25% H₂, 13% CH₄ and 8% H₂S, with a calorific value (lower heating value) of about 11MJ m⁻³. The temperature, reaction rate and the production gas quality were affected by gas losses to the surrounding strata and by uncontrolled water ingress. No water injection was needed.

Over a period of days the consumption of the coal creates a cavity. Eventually the efficiency of the gasification process declines. The gasifier is then extended by retracting the ignition point along the injection well to access fresh coal. The aim is to repeat the cycle until the coal resource between the injection and production well is exhausted, or the production efficiency has fallen to an unacceptably low level. Once the entire tract of the in-seam injection well has been exploited the residual cavities would be flooded with quench water to ensure a permanent extinguished state. This was achieved using natural water inflow at El Tremedal. At any time, reactions could have been arrested by purging the gasifier with N via the injection well or switching off the O₂ flow.

The process of CRIP was shown to be repeatable by the UGE trial during which the coiled tubing was retracted seven times and three ignitions made. Deviation of the injection well meant that only parts of its length were in coal. Possible ignition locations were therefore limited.

3.9 Treatment of the Product Gas

The product gas contained as much as 50% moisture by volume. This unusually high water content arose due to groundwater entering the gasification channel from a breached aquifer and flowing towards the production well. Fortunately, most of it bypassed the reaction zone and therefore did not unduly inhibit gas production.

No pollutants were detected at El Tremedal apart from H₂S which was expected due to the unusually high S content of the coal.

UGE did not plan to use the production gas, therefore the gas was flared.

3.10 Monitoring and Control

In order for the gasification process to be controlled, it is essential that continuous analytical measurement of the product gas stream is available.

The analysis system used in the Spanish trial was designed to measure the composition of the gas stream on a dry basis. Flow rates were measured for the wet and dry gas streams enabling the dry gas/liquid ratio to be calculated. Much of the technical complexity of the system was involved in conditioning the samples, typically taken using retractable probes, with the use of cyclones and filters for particle removal, before they could be introduced to the analysing equipment.

Injection flow rate and composition, temperature and pressure were measured at various parts of the circuit to facilitate control of the gasifier and to ensure pressure and temperature design limits of system components were not exceeded. The manipulation of the following variables allowed the reaction rate and the gas quality to be adjusted within certain limits:

- Injected gas flow rate and composition
- Reactor back pressure
- Production well base temperature
- Safety monitoring and alarm control

Detailed well temperature and gasifier advance data were provided by a fibre optic system. Thermocouples provided fixed-point data.

The monitoring and control system has an important safety role. The basic functions consist of:

- Monitoring the on-line status of process variables
- Adjusting process variables – closed loop tuning
- Monitoring and display of strategic point alarms
- Data processing, storage and display

The monitoring of the injection and ignition system proved to be inadequate as conditions arose unnoticed which led to the well being damaged by an explosion.

Cavity size was estimated from mass balance calculations but the results varied according to the assumptions made (eg water influx).

3.11 Technical Problems Encountered During the UGE Operation

Geological and Hydro-geological

During the gasification trials it became evident that the available coal exploration data was insufficiently detailed when unexpected geological features led to uncontrolled gas losses and groundwater inflows. While geotechnical problems were adequately dealt with, uncertainties relating to the geology of the trial area, and its interpretation, were responsible for major delays.

The hydrogeology is critical. Minor inflows of water into the cavity and the reactor can be accommodated by adjusting the injected water input. Excessively high water flows could reduce the efficiency of gasification due to cooling. The worst case event is the possibility of a major inrush quenching the gasifier.

Experience elsewhere had been that water influx could be controlled by increasing reactor back-pressure. Control was achieved initially at El Tremedal, but when the cavity breached the sandstone roof this process proved ineffective. Subsequently, the water influx seemed to depend more on the cavity development and reactor geometry (Chappell and Mostade, 1998). The implication is that if significant water inflow from the strata cannot be satisfactorily controlled then interaction with aquifers must be avoided at the site selection stage.

Gas and temperature losses to the overlying permeable stratum were responsible for decreases in gasification efficiency at El Tremedal. Although a site selection rather than a technology problem, it indicates the need for overlying strata to have low permeability and an absence of aquifers within the zone of disturbance above the cavity.

Geological exploration is costly but if not sufficiently thorough could prove costly at the drilling stage resulting in serious delays to the start of production and abortive directional drilling. A combination of drilling and geophysical techniques should be used to reduce geological risk. The intensity of exploration required will depend on the quantity and quality of existing data and the complexity of the geology in terms of both stratigraphy and structure.

In addition to geological data, good hydrological and hydro-geological information is also essential. Uncontrolled flows of water into the reaction zone will affect the gas composition and, in extreme cases, could quench the gasifier. Where rock or fracture permeability allows water to flow, they will also allow reaction products to escape into the strata, possibly causing pollution some distance from the reaction zone. The requirements for environmental protection are likely to be rigorous especially where production wells pass through major aquifers. Any gasification whether experimental or commercial should therefore be preceded by groundwater quality sampling to provide a reference basis for assessing whether any pollution has occurred following gasification.

In-seam Drilling

During the drilling of the injection well, the trajectory deviated from the seam base into the underlying limestone. The number of possible ignition locations was thereby limited. The problem arose because the drilling guidance system was too remote from the drill bit. More suitable equipment existed at the time but it was not available when needed.

A very accurate (within 0.4m) interception of the injection and production wells was achieved. Only by further experimentation will it be possible to determine how much of this accuracy was chance and how much was due to the technology and skill of the drilling company.

Directional drilling capabilities and accuracy can be achieved with modern MED surface-guided systems that should be able to obviate the problems of keeping in-seam encountered at El Tremedal. In addition, the linking of injection and production wells, or interception within one metre, must be reproducible and not a matter of chance.

Ignition System

The failure of this system was the cause of an explosion during attempts to ignite the gasification channel for a third time. The ignition and injection monitoring system requires modification to reduce this risk.

The cause of the explosion was the ignition of a methane concentration which had accumulated after the 'pilot' flame at the igniter had self-extinguished.

Had the temperature measuring system (the thermocouple at the ignitor) not been damaged during the previous ignition procedure, the absence of a flame would have been noted. It also seems that there was a failure to detect abnormal flow rates in the injection well indicating possible shortcomings in the process control system.

The main lesson from the total loss of operations which resulted from the ignition incident is the need for redundancy by preparing more than one well pair, even for experimental tests.

Various options for improving the ignition system are proposed in UGE reports:

- Keep the same ignition procedure but change the design of the well services to ensure better protection of cabling, sensors and methane feed.
- Use a perforated liner to remove the need to burn through the liner to ignite the coal, although there is a belief that this could result in uncontrolled ignition at various points along the in-seam borehole.
- Use an electrical ignition device instead of a pyrophoric compound as this may be potentially easier to measure and hence control.
- Include for contingency in the design. Allow for possible failures by installing duplicate systems.

Surface Plant

Problems were encountered with equipment compatibility especially with specialised items of an experimental nature. Some of this may have been exacerbated by bureaucracy during design and procurement. A generic design which specified all the necessary equipment and capacities would be a helpful guide to commercial developers and manufacturers.

3.12 Key results of the UGE trial

The UGE trial proved the technical potential of medium depth UCG and enabled the engineering requirements to be established. Valuable lessons were learnt that will enable engineering risk to be substantially reduced in any future trial.

The UCG process can be operated with stability and flexibility, as input flow has been shown to have a direct relationship to production flow, with little effect on product gas quality. The power output from the gasifier could be rapidly increased or reduced by increasing or decreasing the O₂ flow rate. This turndown capability is encouraging in respect of commercialisation potential, for example, electricity generation applications.

The engineering installations, monitoring and control systems performed well for prototypes.

The CRIP method for moving the ignition point using coiled tubing proved repeatable.

Post burn drilling indicated a disturbed roof zone extending at least twice seam thickness above the gasified zone and a cavity width at least five times coal thickness.

Examination of production pipe-work revealed no corrosion attributable to inappropriate material selection. However, as uncontrolled water influx suppressed bottom hole temperatures and gasifier operations were short-lived, these results are not definitive.

No significant pollution problems were detected. Groundwater flows into the cavity, subsequently recovered at the production well, probably purged the gasifier of residual pollutants and therefore the cavity sampling was not necessarily representative of the general case.

3.13 Shortcomings of the UGE Trial

Gasification was not continued for sufficiently long periods to confirm the sustainability of the production process and to enable the geometry of a completed gasifier to be characterised. The final geometry defines the coal resource available for gasification by a well pair (injection and production well) and is fundamental to financial viability.

The geological conditions did not allow for optimisation of the thermochemical processes.

No attempt was made to assess commercial viability. Although this was not one of the aims of the trial it is an issue which must be addressed to provide a basis on which the value of the applied research can be assessed and the scale of commercially feasible UCG plant determined.

4. GUIDED DRILLING TECHNOLOGIES

4.1 Introduction

Deep, high pressure UCG will rely on guided drilling technology to initiate a well at the surface which will intercept and follow a coal seam, probably for 400m or more, and to establish a link between injection and production wells.

Prior to the Spanish trial, deep UCG trials had been made in France (1981 to 1986) at depths up to 1200m in anthracite and in Belgium (1979 to 1987) at 860m depth in anthracite. Well linking by reverse combustion and hydrofracking were unsuccessful in the French trials. Difficulties were also experienced in the Belgian trial at Thulin in completing the gasification circuit. Reverse combustion failed and a drilling solution was required. The EWG (1989) analysed previous work and concluded that linkage was best achieved by drilling and that this would be easier to achieve by drilling the long injection well before the vertical production well.

Guided drilling technologies have been used successfully for many years within the oil and gas industry. Advances in down-hole measurement and communications technology, coupled with the location of guidance sensors directly behind the drill bit, has resulted in the development of a new generation of guided drilling equipment capable of providing greater accuracy, increased drilling speeds and cleaner hole completions than that available to UGE.

The measurement of position co-ordinates and formation characteristics close to the bit, together with the ability to transmit the information to the surface, allows the engineer to steer the borehole accurately, particularly when combined with steerable drilling systems that can be operated remotely from the surface. As with any drilling operation, problems can be experienced in controlling the borehole within a target horizon depending on the geological conditions.

Recent technological developments include:

- continuous MED of positional and geological parameters
- a range of geophysical sensors to facilitate continual evaluation of formation characteristics and 3-D modelling at the surface
- sensors close to drilling assembly to ensure steering accuracy
- real-time down-hole to surface, and surface to down-hole, data transmission for remote monitoring and steering control
- rotary steerable systems controlled at the surface and with higher drilling rates than down-hole-motor (DHM) systems

4.2 Guided Drilling Technologies

There are various types of guided drilling system:

- DHM with bent-sub assembly or surface steerable unit
- advanced rotary steerable systems, with supplementary DHM if required.

These systems incorporate down-hole monitoring sensors to capture and relay information to the surface, and also to transmit commands to remote steerable units. The basic DHM with bent-sub (a part of the drilling assembly which incorporates a fixed bend) is compared with the advanced rotary steerable technology in Table 3.

DHM Technology

With this technology, rock cutting is achieved by the rotation of the drilling assembly independently of the drill rods.

Down-hole-motors are turbines which use the hydraulic force of the drilling fluid to rotate the cutting bit. Sensors are located behind the motor. The accuracy of steering depends on the proximity of the sensors to the drill head. Older systems in which the sensors are 10m or more behind the drilling tool can be difficult to keep in-seam.

For guided drilling a bent-sub assembly with a fixed angle is used with a DHM. The angle cannot be adjusted during drilling, any changes require the drill assembly to be withdrawn from the hole. Control is achieved by rotating the bent-sub to follow the required trajectory using a combination of pushing and rotating of the drill string. The angle of the bent sub assembly is selected to match the required deviation of the hole.

Rotary Steerable Technology

The drive for the drilling assembly is transmitted from the surface by rotating the drill string with this technology.

Faster penetration rates, due to better cuttings removal compared with DHM's, and greater control of the borehole along the planned trajectory can be achieved using rotary steerable technology. These systems incorporate guidance sensors directly behind the drill bit providing data at the point of drilling. Communications between the down-hole drill assembly and surface allowing the direction of the drill bit to be adjusted remotely without the need to withdraw the rods. The drilling trajectory is changed by the use of ribs or eccentric cams that push against the wall of the borehole or alternatively the down-hole assembly can be deviated using an eccentric cam.

Rotary steerable techniques can produce a smoother borehole than DHM systems as the degree of correction is more easily adjusted. As with many technologies inappropriate use or management of the equipment will result in poor performance.

4.3 Measurement and Guidance Technology

Advances in technology have resulted in the option to incorporating sensors that measure both drilling parameters (co-ordinates) and geophysical properties of the surrounding strata. The quantity and quality of down-hole data will vary for each application depending on the characteristics of the target horizon and immediate strata.

Control of surface to in-seam guided drilling can be further aided by the use of 3-D modelling software to represent and characterise the geological conditions (eg the Sperry Sun 'Landmark' system – see Appendix 3). Results from initial sensor information obtained by the investigation drilling and other physical logging techniques allow a profile *fingerprint* of the conjectured sensor responses for the planned hole to be developed. As the guided hole is drilled, real time information from down-hole sensors is relayed back to the surface to allow a direct comparison and hence correction of the hole trajectory as necessary.

Fundamental to the development of improved guided drilling techniques has been the introduction of data transmission systems which allow information from the down-hole drilling assembly to be sent to the surface, and steering commands returned from surface to the drilling assembly, during the drilling operation.

Communication between the surface and MED equipment uses the drilling fluid or drill string as a transmission medium. Additional information not transmitted to the surface can be stored within the MED assembly and downloaded on the surface following completion of the hole.

Measurement sensors are positioned as close as practicable to the drill bit. Natural gamma radiation and resistivity detectors are commonly used.

A high specification steering assembly may include:

- high resolution resistivity and micro resistivity
- bit speed, inclination and shock sensors
- weight and torque applied to the bit

Sensors incorporated within the MED assembly are selected to match specific formation needs. Logging while drilling (LWD) tools can be used to detect lithological boundaries and measure formation bulk density and porosity during exploration.

4.4 Borehole Stability

Critical to any guided deviated drilling operation is the management of the drilling fluid, particularly where stability of the borehole may be an issue. The preservation of natural fracture permeability in the coal is desirable for promotion of gasification reactions within the coal mass. However, in low permeability UK coals there may be little gain in attempting under-pressured drilling, therefore fluid pressures and compositions can probably be selected to optimise hole conditions and cuttings clearance. Under-balanced drilling can produce data transmission problems where mud pulse systems are used.

Guided and vertical boreholes require permanent and temporary casing to be inserted during various stages of the drilling operation to support the borehole, isolate water bearing strata and facilitate ignition, operation and monitoring of the gasifier.

4.5 Borehole Design

Steered UCG injection borehole designs should include consideration of:

- surface access in relation to the underground target horizon
- surface area for drilling and gasification equipment
- depth and length of hole
- vertical distance to kick off point for deviated section
- degree of deviation and radius
- inclination of the target horizon
- finished internal diameter to accommodate injection, monitoring, control and ignition equipment

4.6 Drilling Contracts

Contracts for drilling services need flexibility to facilitate effective response to unforeseen and changeable drilling conditions but they should be clear in their objective of producing a borehole to the required specification. UCG guided drilling will need to be completed within close tolerances.

The greater the amount of quality geological and geotechnical information provided to the driller, the lower the risk of failure. Guided drilling contractors offer a number of contract variants such as simple day rates, performance and time dependant arrangements and risk sharing. There are potential cost benefits from involving the driller at an early stage of the project to ensure that geological investigations include data acquisition for drilling design. There is common agreement among the service companies on the importance of obtaining good, detailed geological information before starting to drill. Shared risk contracts which enable contractor and client to benefit from rapid completions should be considered for UCG sites.

4.7 Application of Oil and Gas Industry Guided Drilling Technology

The oil and gas drilling industry has experience of drilling deviated and horizontal boreholes in a range of geological conditions. However, conventional reservoir targets are usually thicker than most coal seams. Coal is also sometimes difficult to drill due to its friability. At some locations seams may be prone to splitting and could be difficult to follow. Geophysical sensors may not be effective within the body of a coal seam making accurate horizon control difficult. Techniques which allow the placement of magnetic or seismic devices in the target well to be intercepted should enable a high precision interception to be achieved.

Discussions were held with specialist companies who have developed and applied the latest oilfield guided drilling technologies offshore UK, namely, Baker Hughes, Anadrill (Schlumberger) and Energy Pathfinder Services Ltd (Appendix 3).

Although new rotary guided drilling techniques appear to offer some advantages over down-hole-motors (where only the drill bit rotates and not the drill string), there are contrasting views among practitioners on which approach is preferable for in-coal drilling.

Oil and gas production does not involve in-seam drilling so experience would have to be gained and difficulties with drillability and hole stability in friable coals might be expected. There is a need to compare the benefits of adapting this advanced oilfield technology for UCG with the technologies developed by specialist coalbed methane (CBM) companies for drilling long in-seam boreholes starting from the surface.

4.8 Application of Coal Industry Guided Drilling Technology

Guided drilling technologies have been developed in the USA and Australia for drilling horizontal in-seam boreholes from underground with over 250,000m of in-seam boreholes drilled. Guided boreholes are used to identify geological structures in advance of mine development and also to pre-drain gas from the coal seams.

While the steering technology used, involving a DHM and bent-sub is relatively simple, the success of in-seam horizontal drilling demonstrates the feasibility of drilling long boreholes within a relatively thin, soft, target horizon such as a coal seam.

Few companies are able to demonstrate a track record in drilling surface to in-seam boreholes. Those identified were CDX Gas (USA), Sibra Pty Ltd (Australia) and CMTE/BHP (Australia). Halliburton's drilling subsidiary Sperry Sun also intend to apply their rotary steerable system to drill surface to in-seam guided boreholes. Their experience in transferring oil and gas expertise and technology to in-seam coal drilling would be worth monitoring.

Surface to in-seam guided drilling technology has been developed by CDX Gas (USA) for CBM extraction. Their guided system using under-balanced drilling techniques together with rotary steerable technology to drill a number of in-seam boreholes from a single surface location. Available information reports boreholes of up to 6000m can be drilled in-seam at over 300m per day. Initial results suggest interpretation of down-hole geological formation enables a borehole to be controlled within a 0.5m seam. This surface to in-seam drilling technology is presently been used by US Steel to pre drain coal in advance of mining.

Sibra Pty. Ltd (Australia) have developed surface to in-seam guided drilling technology using a DHM and bent sub assembly to control the trajectory of the borehole linked with a sophisticated high capacity geological formation recognition system. The down-hole communication system uses an electrical connection integral with the drill string.

Innovative surface to in-seam guided drilling technology has been developed by the Australian Centre for Mining Technology and Equipment (CMTE), in collaboration

with BHP Mitsui Coal Pty Ltd. Tight-radius drilling (TRD) technology has been developed to drill a horizontal borehole from a conventional vertical well although a number of limitations are recognised with the current system in terms of borehole length, trajectory control and depth of operation. At the present stage of development it would not be suitable for UCG injection well drilling. However, there could be a role for this technology in linking production wells to misaligned injection wells.

4.9 Relevance to UCG Development in the UK

Drilling technologies are available which are capable of achieving the necessary accuracy for installing and linking injection and production wells for UCG. The technologies currently available are sophisticated and would probably enable complex underground layouts to be achieved subject to the suitability of the geology. The principal uncertainties are the drillability of UK coal seams and the transferability of contractors experience to UK onshore Coal Measure drilling conditions.

Approaches were made to a number of specialist drilling companies during the course of this study to determine the current potential and limitations of state-of-the-art equipment. The companies with the most modern guided drilling technology have experience of conventional reservoir drilling but not necessarily of the more difficult in-seam drilling. In fact, they are concerned about the possible difficulties associated with longholes in coal after bad experiences when encountering coal during oil and gas exploration and development. Specialist CBM drilling contractors may have the necessary experience of coal but not of UK geological conditions.

5. ENVIRONMENTAL IMPACT AND ITS CONTROL

5.1 Introduction

The environmental effects of the UCG process are perceived as being fairly low as the main product of the process is gas and any by-products are either left in the ground, can be removed by conventional processes or can be re-injected back into the seam. Hence, the environmental impacts of mining and also ash disposal are totally negated. However, there are some significant issues which still remain, particularly the effects of the process on surface and subsurface environments.

Most of the knowledge related to the surface and underground environmental impacts of UCG comes from previous trials such as those held at Hoe Creek, Rocky Mountains Trial (Hanna), Huntly, Rawlins, Thulin in Belgium and the El Tremedal trial in Spain. The trials at Hoe Creek in the Powder River Basin, Wyoming are particularly well-documented.

The detailed studies have all been done on shallow UCG sites with relatively small gasifiers. In the absence of deep testing other than El Tremedal it is the best information available. The underground impacts observed at shallow sites are likely to be substantially reduced at depth due to lower strata permeability conditions.

The main environmental issues concerning UCG are:

- Atmospheric emissions
- Surface water
- Drinking water pollutants
- Noise
- Site operations
- Groundwater
- Subsidence

5.2 **Surface Impacts**

Atmospheric emissions

Atmospheric emissions could occur as a result of both surface and subsurface operations. The main emissions linked to the coal gasification process include CH₄, CO₂, CO, H₂, S, organic N₂, H₂S and NH₃ and would be under high pressure (5.3MPa in the case of the Spanish trial). The pollutants need to be separated from the product gas and this can be done at surface using proven conventional technologies (DTI, 1999). Minor SO₂ and reduced NO_x would be released into the atmosphere from a power generation plant. Significant amounts of CO₂ are produced via this process and sequestration would need to be considered.

CO₂ Sequestration

An integrated UCG power generation scheme could approach zero emissions by separation of CO₂ at high pressure and pumping the gas underground. Residual gasification cavities might have a limited capacity for CO₂ due to caving and compaction reducing the available volume, although a theoretical study of the residual porosity may be worth making. Some adsorption will take place in the coal exposed at the edge of the gasifier but the sorption characteristics may have been heat-altered. These effects could be investigated in the laboratory. A potentially larger repository may be provided by seams in the strata directly above the cavity. Any seams in the strata up to 150m above a caved gasifier could be disturbed (Hettema et al, 1997) creating conditions favourable for CO₂ injection and enhanced coalbed methane (ECBM) recovery. In practice, the height of the zone of disturbance would depend on gasifier width and could be estimated using empirical rules already established from studies of gas emission above shortwall and longwall coal faces of different lengths.

CO₂ sequestration would be an additional process cost. For commercial acceptance, the cost would have to be offset by emission credits or justified to offset an environmental penalty.

Any enforcement of CO₂ sequestration arising because practicality had been established, could result in a competitive disadvantage compared with alternative fossil fuel sources, thus retarding commercial application.

Surface Water

Surface water can be affected by UCG operations if pumped groundwater is discharged into local water courses, if groundwater can connect with the surface via springs or if there is any spillage of fluids during drilling or site operations. Groundwater is only likely to affect surface water quality if it is contaminated with pollutants. In the case of the Spanish trial, the water pumped to the surface was classed as toxic because of its phenol content (Green, 1999). Hence it is necessary to monitor the quality of both the ground and surface water and have treatment facilities available. The spillage of drilling muds or other fluids during site operations can be prevented by the use of a variety of simple techniques including bunding of oil/fuel storage areas, the installation of impermeable membranes and provision of drainage to an appropriate sump.

Human Impacts

There are a variety of different operational procedures that might have an anthropogenic impact, including noise, dust, nuisance and drinking water pollution. Noise, dust and nuisance could be generated by site traffic and from the drilling operations. These are likely to have a relatively low impact on the environment and can be reduced significantly by correct planning.

Drinking Water Pollutants

Pollutants are generated by the gasification process and these could impact on man if allowed to contaminate the drinking water supply, either via surface or groundwater or if they escape to the atmosphere. The three most important factors related to pollutants are their toxicity, persistence and mobility. Toxicity is defined as the potential of that contaminant to cause adverse health effects if consumed by humans. Persistence represent the ability of the chemical to remain unchanged in composition, chemical state and physical state over time and mobility is the capacity of the pollutant to migrate.

Pollutants that could be generated include benzene, NH₃, nitrate, phenols and pyridine (EPA, 1999). The half-life of benzene in groundwater is thought to range from 240 hours to 17,000 hours (EPA, 1999). Nitrate is persistent in aerobic environments but breaks down to N gas in anaerobic conditions (EPA, 1999). NH₃ is persistent in groundwater if dissolved O₂ levels are low but will generally convert to nitrate when dissolved O₂ levels are higher (EPA, 1999).

Detailed studies at a shallow UCG trial site in the USA showed that health risks from benzene and phenols to residents in the area surrounding the site were low (see Appendix 4). The Spanish trial also showed no evidence of surface water contamination.

Noise

Site selection, particularly proximity to residential dwellings, would determine the noise impact of a UCG site. The cumulative effects of noise levels resulting from UCG operations are not expected to be noticeable to residents or visitors within the area except during construction activities or around compressor facilities. Noise levels

would be temporarily elevated above the general background noise during construction of facilities and would be relatively short-term.

The main sources of noise are likely to be from drilling operations (eg motors, compressors, pumps as well as steel handling, tripping the drill string) and plant. It is likely that the highest operational noise levels would occur around compressors. Noise has been measured at typical pipeline compressor units (USDI BLM, 1981). A noise level of 87dBA at 15m from a compressor station can be expected. This would decrease to 61dBA at about 300m from a compressor and 55dBA at about 600m away. The impact can be reduced by applying simple noise minimisation procedures such as acoustic enclosure for the compressor and other noisy equipment on site as necessary. Compressor noise can be reduced by about 10-20dBA by enclosure (USDI BLM, 1981).

Site Operations

For any UCG activity, whether it be a trial or a commercial operation, there will be a certain amount of surface activity, including drilling and land preparation. This will occur mostly at an early stage of the process and will reduce during the production phase. It would mainly involve movement on and off-site of equipment and materials and some soil excavation. The impact of these facilities is less than for conventional mines or power plants because the primary process is located underground and there is no need for coal storage or transport facilities. Site selection would form an important part of the process to minimise any surface impact.

5.3 Subsurface Impacts

Groundwater

Possible effects on the groundwater regime as a result of UCG operations include hydrological and groundwater quality changes. Hence site selection is an important consideration and needs to be chosen so as to have minimal or no impact on local aquifers. The principal contaminants that might influence groundwater quality are the by-products produced as a result of coal burning processes; these could include benzene, toluene, ethylbenzene, and xylenes (BTEX), phenols, coal ash and tars, aromatic hydrocarbons and sulphides, NO_x, NH₃, boron (B), cyanide, CO and H₂S. Current indications are that these pollutants will be left in the ground or carried to the surface by the product gas, where they can easily be removed using existing technology.

However, where aquifers with good porosity and permeability characteristics are located stratigraphically close by it is possible that cavity collapse could lead to opening of fractures and allow the escape of pollutants into the local groundwater regime. Interaction of the gasifier with aquifers and potentially fractured ground through which migration could occur can be avoided by selecting deep seams for gasification away from any current or previous mining activity. In the UK Coal Measures the amount of groundwater circulation diminishes with depth. Nevertheless, it would be essential to have a good understanding of the geological and hydro-geological conditions prior to carrying out UCG tests.

Comprehensive groundwater monitoring at a shallow UCG site in the USA identified contaminated groundwater plumes where tests at elevated pressures had been carried out 55m below surface. Remedial treatments involving air flushing (sparging) and biostimulation were employed in the affected areas. Further details are provided in Appendix 4.

The knowledge gained from trials in the USA such as Hoe Creek was applied at El Tremedal in Spain. Here underground conditions were kept as close to hydrostatic pressure as possible to try and avoid underground water influx or gas losses through the strata. Analysis of samples taken from the cavity revealed low concentrations of phenols, ammonia and sulphides in the groundwater (DTI, 1999). These act to raise the chemical and biological O_2 demand and raise the pH levels of the water. The water from the cavity was pumped to the surface and treated with the oxidising agent hydrogen peroxide (H_2O_2) before discharge.

At depth in UK Coal Measures, pollutant escape problems are unlikely to occur and risks can be minimised by site selection, hydrological and hydro-geological studies and control of pressure during gasification.

Subsidence

A cavity is created as gasification proceeds. As it widens, the roof collapses. The caving process will depend on the mechanical properties of the rocks, geological and thermal stresses. By analogy with shortwall and longwall methods of mining, subsidence will be expected depending largely on the geometry of the cavity and depth. In general, as extraction depth increases, surface subsidence decreases.

Subsidence observations on shallow test sites in the USA (Appendix 4) are of limited relevance as the void migration mechanisms which can cause surface instability (as with shallow mining) are not important at depth.

Following the UCG trial in Spain, drilling indicated that gasification had produced a cavity that affected the sandbody above the coal (Green 1999). The width of the cavity was estimated to be at least five times the thickness of the seam and the height was twice or more the thickness of the seam. There has been no apparent surface subsidence and the small size of the cavity produced makes this unlikely.

Current data all relate to test sites which can be regarded as relatively small scale. Full scale operations would produce more extensive cavities that could result in surface subsidence.

5.4 Monitoring and Control of Environmental Impacts

Hydrological, geological and hydro-geological investigations and an environmental assessment would need to be carried out prior to any UCG operations. To achieve this to the satisfaction of the regulators some borehole sampling in and around the site may be required.

A trial should therefore incorporate a detailed environmental monitoring programme to establish initial conditions and compare them with those detected during operational

and post-closure stages of the UCG project. This knowledge is required to design environmentally acceptable commercial schemes. Groundwater level, groundwater chemistry and dissolved gases should be monitored to establish baseline conditions prior to any other form of experimental drilling.

5.5 Hydro-geology

The hydro-geology of the Carboniferous succession is dealt with in a comprehensive manner in the BGS/Environment Agency (EA) Minor Aquifers report (Jones et al. 2000) and the following section borrows heavily from this work. In addition, a brief overview of the hydro-geology of the UK coalfield areas is provided in Appendix 5.

The main influences on the hydro-geology of coal-bearing successions are:

- Lithology
- Fractures (faults and joints)
- Folds
- Lateral extent of the aquifers
- Effective aquifer thickness

Lithology

The Carboniferous forms a multi-layered succession which include mudstones, sandstone, limestones and coals. The limestones and sandstones generally act as aquifers and the mudrocks acts as aquicludes or aquitards (Jones et al. 2000). In some instances well-cemented sandstones and/or limestones can also act as aquitards. The primary porosity of the Carboniferous sandstones at surface typically range from 10 to 15%, with the limestones being of a much lower porosity. Permeability is also greater in the sandstones but varies considerably due to differences in cementation. Both porosity and permeability decrease with increasing depth of burial due to the effects of compaction and cementation. At shallow depths, the degree of weathering influences these two features, with increasing weathering generally increasing porosity and permeability values.

Porosity and permeability data on Coal Measure sandstones are summarised in Appendix 6.

Fractures

Most water flows in UK coal workings are associated with aquifers or faults intersected by mining rather than from the seams themselves (Creedy 1994). Where intergranular permeability is low, groundwater predominantly moves through fractures. Joints are present in all strata but are more likely to be open in the arenaceous and carbonate beds. As these also act as the aquifer horizons then groundwater flow can be influenced by their size and extent of the fractures, their degree of interconnection, and whether they are open or closed. Permeability often increases in the zone of deformation surrounding faults, allowing groundwater to move along these zones. However, where there is a significant fault gouge, flow can be retarded. Where sealed faults have

compartmentalised the aquifer there is likely to be only limited recharge, thus restricting yields from the aquifer.

Folding

The degree and extent of folding can play an important role in controlling groundwater movement; this phenomenon has been documented from the East Midlands area (Downing et al. 1970; Gray et al. 1969). Extension along the crests of anticlines has led to the opening up of joints. This has allowed groundwater infiltration and its migration down dip into adjacent synclinal areas. Mine workings in these synclines are well known to be wetter than the adjacent anticlinal areas (Downing et al. 1970; Gray et al. 1969).

Lateral Extent of Aquifer

Within the Carboniferous, both the limestones and sandstones, but particularly the sandstones can occur in linear belts with restricted lateral extents. This places a finite limit on the yield from such aquifers.

Effective Aquifer Thickness

The interbedded nature of the Carboniferous succession combined with often poor data sets means that it can often be difficult to measure the actual effective aquifer thickness or even to pinpoint actual yield horizons.

5.6 Key Environmental Issues

Interactions of UCG cavities with aquifers and the potential for pollutants to migrate away from the cavity are the primary issues to be addressed in an environmental impact assessment. In the UK, onshore UCG production wells at many locations will pass through major aquifers. It will be essential to demonstrate that these aquifers can be protected from unacceptable thermal and chemical pollution. The environmental benefits of integrated UCG power generation can be emphasised by comparing with conventional underground mining and power station processes as listed in 1.1.

6. COMMERCIAL FEASIBILITY

6.1 Introduction

The European Working Group (EWG 1989) report compares the financial viability of fuel gas production, methanol production and electricity generation, the latter proving to be the best application. Estimated electricity production costs at depths of 1000m and 2000m varied from 0.040-0.151 ECU kWh⁻¹ depending on lateral gasifier growth. Gasifier widths from 30-50m were assumed.

A simple integrated UCG process and accounting model was developed for this project to determine whether an integrated UCG – power generation process was likely to be commercially feasible using currently available technology, and also to determine the smallest potentially viable scale of operation.

An accounting approach was adopted which assumes that every piece of equipment is purchased, constructed and commissioned on the first day of the project (including the drilling operations required for the entire life of the project) and that production is instantaneous. However, these costs are spread over the life of the project by incorporating them into an annual 'depreciation' cost, which is quoted as part of the annual production costs. Thus, the result will not be too dissimilar to the rolling drilling programme that would be undertaken in practice. The depreciation cost allows for the cost of borrowing by applying an interest rate annually.

The UCG process model assumes that the volume of coal that can be gasified in a simple linear reactor depends on the seam thickness, the reactor length and an equivalent width. Conceptually, the equivalent width would be the average width of the gasifier if the cavity was assumed to be rectangular. In practice, some areas of coal may become isolated as the gasifier grows laterally due to irregular roof caving and resulting flow re-distribution effects. Its shape and extent may also be affected by varying strengths of roof strata, permeability of caved material in the gasifier and ignition initiation locations selected during CRIP manoeuvres.

The process model assumes a fixed, moderate heat value gas (user specified, expected to be in the range 11-15MJ m⁻³ lower heating value) is produced suitable for fuelling an open cycle gas turbine power generation scheme.

6.2 A Cost Model

Initial Capital Costs

Detailed cost tables were prepared drawing on information from the Spanish trial, service companies, manufacturers and suppliers. Drilling and completion, ancillary equipment, O₂, gas cleaning and power generation plant were all included. Costs were corrected to December 2000 using the retail price index. Standard chemical engineering factors were used to adjust factory supplied units and packaged installed units to a common installed basis taking account of material, labour and indirect costs. A cost capacity factor was used to account for economies of scale when changing plant sizes. Costs were verified by comparing ratios of various cost types (factory built equipment, labour, material direct and indirect costs) with published ranges.

A drilling cost model was devised to estimate the costs of completing a linear gasification circuit using current guided drilling technology. The cost of establishing a linear gasifier at about 750m is estimated at £1.2 million. Guided drilling costs appear to be generally two to three times higher than vertical drilling costs. However, drilling costs can be highly variable depending on the site location, strata and target horizon.

Other costs associated with the drilling of the injection borehole and production well, and those for the UCG process including instrumentation, coiled tubing and CRIP ignition unit were identified and included as a fixed sum per pair of boreholes.

The UCG cost model calculates the number of injection and production wells (well pairs) required for the duration of the project (10 years) depending on the life of each gasifier which in turn depends on the volume of coal accessible.

The drilling costs are considered by some to be too high but possible exploration drilling costs that have been excluded could result in an even higher final drilling cost in some instances.

Scenarios

The integrated model was used to examine two small-scale, open cycle gas turbine power generation options:

- 8MW_e
- 50MW_e

The coal seam thickness and gasifier area was varied assuming a fixed revenue for any electrical power generated.

Results were assessed in terms of production cost per unit of electricity before interest and tax. The model excludes grid connections, any royalties and land acquisition.

The main cost items are shown in Table 4.

The estimated costs for the turbine-generator packages were £6m for the 8MW_e and £25m for the 50MW_e. The estimated drilling cost to complete a single linear gasifier circuit was £1.41m (800m depth, 400m gasifier channel in-seam).

Tables 5 and 6 show the electricity production cost (before tax and interest) for various linear reactor sizes and fuel gas heat values, for an 8MW_e and 50MW_e scheme respectively, at a fixed electrical conversion efficiency. Sensitivity analysis indicated that gas heat value and electricity conversion efficiency are the two most critical parameters. Table 7 shows the benefit of increased turbine efficiency that might be expected with the larger installation.

These results indicate that an 8MW_e scheme would be marginal at best, unless electricity prices of 5p kWh⁻¹ or higher could be obtained. However, a 50MW_e scheme would appear to show promise. Robust costs were used in the model, if these were relaxed to reflect possible savings as a commercial system was developed and also drilling risk reduced, then smaller scale projects could become feasible.

Since 1995, industrial consumers have typically paid 3.6-4.3p kWh⁻¹ for electricity. Prices obtained by small-scale generators vary throughout the day, depending on which part of the demand cycle they supply. Few price data are available, but a suggested average range is from 2-3p kWh⁻¹.

Cost savings could be made by branching a series of injection wells from a common vertical section into the same seam, or into different seams. The use of a production well for multi-seam extraction would be difficult due to the complexity of the tubing installations but a single well could probably produce from a series of radial injection wells, provided a pillar was left around the production well and the diameter was sufficient to prevent throttling of the gas flow.

Another approach may be to simulate longwall retreating with the gasifier, comparable to the underground mining construction methods used in China, but using drilling technology instead.

6.3 Project Scale for Commercialisation

New technology is of no economic value unless commercial operators are prepared to apply it and develop a sustainable business. The technical risks associated with UCG are presently high so strong incentives are needed to attract the commercial sector.

Preliminary cost modelling indicates that relatively small UCG power generation schemes could be profitable. Rather than consider the long-term goal of 300MW_e power station schemes envisaged by the EWG, there could be a medium term opportunity to stimulate commercial development of small-scale UCG power generation schemes within the embedded generation market. Preliminary enquiries indicate there may be an interest at a scale of 50MW_e. The business risk to the generating company could be reduced by incorporating a natural gas supply in the scheme. Small-scale UCG production could provide a natural diversification opportunity for existing CBM companies, thus nucleating commercial development of the technology.

6.4 Commercial Interest

In order to gauge the level of interest and knowledge regarding UCG a survey was conducted of consultants, service companies, suppliers and potential developers. Of the 26 respondents, five claimed substantial knowledge of UCG and 14 had little or limited knowledge of the technology.

An interest in R&D was expressed by 11, with seven expressing a willingness to invest. Six had no wish to become involved with R&D. The general view was that UCG is a medium to long-term development. Interestingly, 10 respondents (9 from UK) saw opportunities overseas and five were only interested in development in the UK.

The survey showed a need for wider dissemination of basic information on UCG processes, the technology and potential benefits.

7. WORLDWIDE REVIEW OF UCG DEVELOPMENTS

7.1 Introduction

Historical developments in UCG still have some relevance to the deep high-pressure process envisaged for European application. Past experiments provide data on the gasification of different coals, environmental pollution hazards, use of produced gases and engineering processes. In addition, there may be some commonality of equipment relating to surface injection, gas production, monitoring and processing that could reduce development costs for manufacturers and suppliers and extend their markets. UK gas turbine manufacturers in particular may benefit from a wider interest as shallow UCG technology projects overseas could provide a market ahead of developments in Europe.

The EWG report (1989) summarises world-wide activity prior to 1989 involving some 17 trial sites in six different countries and can be consulted for further details.

7.2 Australia

There are a number of UCG research projects presently being undertaken in Australia. The Commonwealth Scientific and Industrial Research Organisation (CSIRO) are preparing a practical model of UCG that can reform real-time predictions of gasifier behaviour and integrate into a model based control system, to optimise gasifier performance. Development will also focus on providing an aid to the design of UCG field layouts. Other work includes the use of CFD modelling techniques to predict the behaviour of structures, walls and rubble, under various conditions.

CSIRO Petroleum Resources are involved with research work connected to the ancillary processes in a low emission UCG process. The work forms part of a proposal by a commercial operator for government funding under the greenhouse gas abatement program. The proposal involves UCG for power generation with CO₂ separation and aquifer sequestration.

A commercial trial is presently being undertaken by Linc Energy with assistance of a local power company (CS Energy) and government support. The trial started in December 1999 at a site near Chinchilla, 200km west of Brisbane, using Russian technology. The coal seam is about 8m thick at a depth of about 130m. Proposals are being considered for a 40MW demonstration power plant later next year

It is unlikely that deep UCG will be of immediate commercial interest in Australia as there are substantial coal reserves at 200m to 400m depth. However, similar drilling, process monitoring and control and end-use technologies will be applicable.

7.3 China

The government of China regard UCG as an important clean coal technology. Coal is the most important energy source in China but there is widespread concern about the pollution caused by burning coal and the environmental damage caused when mining it.

In China, access to the coal for UCG is gained using underground mining methods, usually existing workings. The primary aim is to recover remnant coal from exhausted mines prior to total abandonment. Underground 'kilns' are constructed and then sealed from the ventilation circuit. The identified UCG resource in China consists of unworked coal and pillars in abandoned mines amounting to some 30,000 million t.

The Underground Gasification Engineering Research Centre at the China University of Mining and Technology (CUMT), Beijing, has developed a variant of the shallow UCG process. Following trials at Xinhe mine, Xuzhou (1994) and Liuzhang mine, Tanshan (1996) a *long tunnel, large section, two stage* method has been devised capable of producing a gas with heat values in the range 12-14MJ m⁻³ (calculated) and a H₂ content of around 60%. The process involves oxidation in an air-blown first stage to raise the temperature of the reactor then injection of steam which is decomposed on contact with the heated coal to form H₂ and CO. The long gasification tunnel (>200m) aids heat transfer to the coal seam and the large section (>3.5m²) ensures sufficient coal

in the reactor to maintain the stability of the process. A production flow of 1500-1900m³ h⁻¹ was achieved at Xinhe and 2100-2900m³ h⁻¹ at Liuzhang mine. The process is monitored and controlled from the surface. Currently, trials are in progress at Xinwen, Shandong at two mines, Suncan and Xiezhuang. Suncan supplies 20,000m³ of gas per day to 10,000 households and also industrial consumers. Subsidence and groundwater quality are being monitored.

The conventional Russian technology, with some modifications, is also being applied in China. Tests to date have all involved air-blown systems producing gas with heat values in the range 4-6MJ m⁻³. Trials of 80 to 120 days duration have been undertaken at Yilan, Heilongjiang and Yima Hebi and Xinmi in Henan (1998 to 2000). Two projects are under construction in Henan and Sichuan, both air-blown systems.

Burners for low and medium heat value gas have been developed for steam raising, domestic cooking, domestic hot water and industrial heating. Consideration is now being given to a small-scale power generation project, with a capacity of 15,000m³ h⁻¹ and O₂ injection of 3000m³ h⁻¹ to produce a gas with a heat value of 10MJ m⁻³. Options being evaluated include the conversion of a coal boiler to coal gas in an existing power plant, installation of a purpose-made gas turbine and also combined cycle technology. Talks with turbine manufacturers indicate that suitable adaptations can be provided.

As a pollution control measure, the government of China has ordered the closure of 4GW of coal-fired small-scale (<50MW_e) mine-mouth power stations by the end of 2002. The feasibility is being examined of retrofitting some of these stations with UCG powered gas turbines and upgrading them into combined cycle plants.

A project due to start next year in Shanxi Province involves the use of UCG to provide raw material for synthetic ammonia and high purity H₂ for gaseous phase carbon black manufacture. Methanol production is another use for UCG production that is under consideration. There are plans to add methanol to motor fuel to reduce exhaust gas pollution. This would create a demand for 20 million t of methanol each year.

A UK-China UCG technology transfer project is currently being sponsored by the DTI to promote collaboration in the development and commercialisation of UCG technologies.

7.4 Japan

A feasibility study has been undertaken for a UCG trial and a 55km² site area selected (Shimada et al, 1994). Predictions were based on analysis of field data from UCG trials in the USA. The study identified the largest cost elements as drilling and O₂.

7.5 New Zealand

A UCG project was undertaken in December 1994 in the Huntly coal reserve situated 120km south of Auckland. Injection wells were linked to a production well. The test was carried out over a 13-day period and approximately 80t of coal was gasified. CRIP techniques were employed. The results were analysed to provide a design basis for the next stage of development.

7.6 Russian Federation

Russia has developed considerable experience in shallow (<200m) UCG technologies over many years following the commencement of trials in 1933. Scales of operation have been up to 300MW_e equivalent. Gas has generally been locally distributed for industrial use. In the early 1960's five *Podzemgaz* experimental UCG gas production stations were operating although only two; the Angren station in Central Asia using brown coal and South Aba in the Kuznets basin using hard coal were operational by the early 1990's. In total some 15 million t of coal have been gasified underground generating 50 billion m³ of gas. This compares with 50,000t gasified experimentally in the USA.

There are proposals for development of UCG production stations in the brown coals of the Uglovsk basin with capacities of 1000t of in situ coal gasification per day (Gaidaichuk and Borisov, 1992).

UCG research and projects have focused on a range of different coals at relatively shallow depth (less than 200m). Initial UCG experiments used air injection techniques to produce a fuel gas with calorific values from 3.3-4.2MJ m⁻³. Use of steam and O₂ injection increases the calorific value of the fuel gas to 10-12MJ m⁻³ (Kreinin, 1992).

Research work has not only focused on UCG production technologies but also on the downstream process and end use of the gas. The Mining Institute in Dnepropetrovsk is researching the use of UCG technology for the production of gasoline, methanol and other chemicals (Kolokolov and Tabachenko, 1992). The extraction and use of heat from the fuel gas produced by UCG has also been examined.

Groundwater pollution studies have been carried out at the Yuzhno-Abinsk station before and after gasification. The results suggest that phenol concentrations in the spent reactors achieved a maximum of 0.17mg l⁻¹ but in the surrounding area, water sampled from 18 monitoring boreholes contained 0.0007-0.0042mg l⁻¹ phenol (Kreinin and Dvornikova, 1994). Thermal pollution of groundwater was observed.

Environmental monitoring at the Yuzhno-Abinsk *Podzemgaz* station in the Kusbass showed an increase in mineralisation, phenols and water temperature but it was concluded that water pollution during in-situ gasification was of a local nature and characterised by admissible concentrations of noxious compounds.

Novel applications have been identified such as the development of mobile UCG units capable of supplying gas to remote agricultural areas. These would involve the drilling of a limited number of boreholes supplying fuel gas to a local community or consumer. This approach is analogous to direct supply of methane from abandoned mines to customers from boreholes drilled on their sites proposed in the UK.

Research associated with UCG technologies has included mathematical modelling of the gasification process. A model has been developed which takes account of the principal gaseous reactants and products in a gasification channel of known geometry and water influx. The model predicts gas outputs using air injection at various flows and pressures. The results of the model are reported to be in good agreement with measured data from UCG trials (Kreinin and Shifrin, 1993).

Other research has assessed the effects of UCG on the immediate strata. Results indicate the pattern of roof deformation in UCG and the filling of cavities with caved rocks is intimately linked with the physical, mechanical and thermal properties of the rock. At temperatures of 1000-1400°C rocks may deform, swell and expand (Den'gina et al, 1994). In general, rocks cooled after heating (annealed) have improved strength properties.

7.7 USA

UCG technologies have been tested in several areas of the USA over the past three decades with more than 30 experiments conducted between 1972 and 1989 in various mining and geological conditions but all at depths of less than 300m. With the exception of one trial site, experimentation has involved sub-bituminous coals. The basic details are summarised in Appendix 2 and further information on environmental studies is provided in Appendix 4.

UCG trials, subsequent environmental monitoring and other laboratory research work have demonstrated that shallow UCG technology is both technically and environmentally feasible. Research has highlighted the importance of assessing the geological and hydro-geological setting for UCG. Any commercial development will be driven by demand for fuel gas, derived products and energy prices (Oliver and Dana, 1991).

Parallel to the UCG trials, 3-D computer models have been developed. CAVSIM simulates the evolution of a cavity from near start up to exhaustion. The model predicts the effects of rubble (caved roof) consolidation on the injection process and drainage of water into the gasification zone from adjacent strata (Britten and Thorsness, 1989).

UCG research in the USA has resulted in the following contributions relevant to the current status of development in Europe:

- Providing concepts established from site observations for cavity growth modelling
- Development and demonstration of CRIP techniques
- Use of guided drilling techniques to establish the gasification channel
- Gasification of bituminous coal (Pricetown)
- Post-gasification underground environmental impact data
- Highlighting importance of hydro-geological characterisation.

Regulations are in place in the USA requiring permits for fossil fuel recovery wells.

7.8 Former Yugoslavia

UCG trials have been proposed in the steep coal seams and oil shales in the Aleksinac basin. Access to the coal would involve two boreholes. Designs were being prepared for the simultaneous gasification of coal and overlying oil shales (Mijatovic et al, 1993).

7.9 Other Countries

UCG has also been examined in Bulgaria, Former Czechoslovakia France, India, Italy, Morocco, Oman, Poland, Romania, Thailand and Turkey. Few details are available and in most instances work has not progressed beyond feasibility studies.

8. POTENTIAL GEOLOGICAL RESOURCE FOR UCG IN THE UK

8.1 Introduction

Substantial coal seam resources for underground gasification are likely to occur both onshore and offshore in the UK. Although the technical complexity of offshore UCG has yet to be considered, the existence of a coal resource and an established oil and gas exploration and development infrastructure means the possibility merits consideration.

8.2 Onshore Area

Geologically, the best prospects for UCG in the UK are likely to be unfaulted, moderately or gently dipping seams, at least 2m thick at depths from 600m to 1000m. A detailed study of each coalfield, to screen for the above criteria, is beyond the scope of this report as it would require detailed study of local geology and mine plans to ascertain where target seams have been mined. The aim of this report is to provide broad indications of the coalfield areas in which UCG might be an option from a geological viewpoint.

The broad characteristics relevant to UCG of the main coal-bearing areas of the UK are tabulated in Appendix 7 and the locations of the coalfields are shown in Figures 5, 6 and 7.

8.3 Offshore Area

A practical constraint on the exploitation of offshore coals would be the method and cost of access. It is helpful, therefore, to divide the coals in the UK offshore area into two groups:

- Coals accessible from land or near-shore
- Coals accessible only from offshore installations

Coals accessible from land or near-shore

Coals up to about 8km offshore are technically accessible via long reach development wells similar to those used at the Wytch Farm oilfield in Dorset.

With the exception of the offshore continuation of the Brora Coal, all the offshore coals that are accessible from the land or the nearshore zone are Carboniferous Westphalian or Namurian coals, similar to those that are mined onshore. Figures 5, 6 and 7 show the depth and distribution of these coalfields and brief details are tabulated in Appendix 7.

There are eleven main areas of possible interest:

1. The Firth of Forth (the subsea continuation of the Lothian and Fife coalfields)
2. Offshore Northumberland and Durham (the offshore continuation of the Northumberland coalfield, which has partly been mined)
3. Offshore continuation of the Scremerston Coal Formation (this is poorly known)
4. A small area of concealed Coal Measures beneath Robin Hood's Bay
5. Offshore from the east coast of England, roughly between Bridlington and Skegness.
6. Adjacent to the NE coast of Norfolk. Boreholes suggest this does not contain any coal onshore.
7. Off the Kent coast approximately between Pegwell Bay and Folkestone (partly mined)
8. In the Bristol Channel, where there is a small continuation of the Bristol Coalfield
9. In Swansea and Carmarthen Bays, where there is an offshore continuation of the South Wales coalfield
10. Around the eastern margin of the East Irish Sea, offshore from the Vale of Clwyd, Point of Ayr (which has partly been mined) and the Dee and Mersey estuaries.
11. Offshore West Cumbria (the offshore continuation of the West Cumbria coalfield) and possibly beneath the Solway Firth (the latter is not proven).

Mining has already extended from onshore to the near offshore in some of the areas. Additionally, some are covered by mining licences.

Coals Accessible from Offshore Installations

Some seams are accessible only from fixed offshore (oil and gas) platforms or via deep water drilling rigs.

Major areas of Westphalian Coals occur in the southern North Sea and Irish Sea. Their distribution and depth is shown in Figure 7 and Figure 5 respectively. Technically, if the individual seams are thick enough, these huge areas of Coal Measures have potential for exploitation from offshore gas platforms.

A maximum cumulative coal thickness of 74.4m of coal in 65 seams is recorded in well 44/28-2 in the Westphalian of the Southern North Sea and this well did not penetrate the complete Westphalian succession.

A maximum cumulative thickness of 33m of coal from 30 seams is recorded in Irish Sea well 113/26-1 in the Keys Basin (Knight, Dolan & Edgar 1994).

Major coal and lignite-bearing formations of Jurassic and Paleogene age have been found in the deep sedimentary basins of the North Sea. There is a technical possibility that some of these coals could be accessed from existing offshore oil and gas platforms. Apart from these major coal-bearing formations, many other formations on the UK Continental Shelf contain thin impersistent coals or single coal seams (Knight, Dolan & Edgar 1994). For example, thin Early Cretaceous coals occur in beds of Wealden facies in the English Channel and St George's Channel, and Tertiary coals occur in small basins off the SW of England and Wales. In many cases, either the coals they contain are in very thin and discontinuous seams, or their distribution is poorly known. A comprehensive review of offshore coals is needed to establish the true resource potential.

The most significant offshore coal-bearing formations are the Beaulieu Member of the Dornoch Formation (early Eocene), the Firth Coal Formation (Carboniferous) and the Pentland Formation (Jurassic). These are briefly described in Appendix 8, along with some of the other, well known but less important, coal-bearing formations for comparison. A comprehensive description of the coals themselves (eg rank, quality) is beyond the scope of this report.

The location of the most important coal-bearing formations and some example wells are shown in Figures 1-10 of Appendix 8. In these figures, the UK offshore wells are numbered by Quadrant and Block and then in the order they were drilled, eg well 16/18-1 was the first well to be drilled in Quadrant 16, Block 18. The Quadrants are numbered on the location maps. The Blocks are numbered in rows from left to right, ie Blocks 1-5 are on the top row of each Quadrant, Blocks 6-10 beneath these, and so on.

8.4 General UCG Prospects in the UK

Based on geological criteria alone, there would appear to be a substantial onshore coal resource that could potentially be exploited using deep UCG technologies. Near shore resources merit further investigation as they may offer attractions in terms of access and lack of surface impediments. At first sight the thought of gasifying coal at remote offshore sites around Shetland and Orkney seems far-fetched. However, given that the infrastructure to drill guided boreholes, produce and transport gas is already in place, as well as the skills and mentality to tackle difficult reservoir engineering problems, it could represent an opportunity. The limiting factor could be financial viability rather than engineering practicality.

9. REGULATION OF UCG ACTIVITIES IN THE UK

9.1 Introduction

The technology cannot be developed or applied without the agreement of the coal owner, local planning authorities and the EA. Operations must be compliant with current health and safety legislation which in turn must be developed to accommodate the new technology.

9.2 Coal Ownership

The Coal Authority is the coal owner and has a statutory obligation to encourage the economic exploitation of coal in the UK. It is also the natural body to license access and use of coal for underground gasification in a similar manner to conventional coal mining.

The 1994 Coal Act states the powers of the Coal Authority, these included the licensing of coal within territorial waters. This has been assumed to be 12-15 miles offshore. Section 8 identifies other relevant legislation regarding the extent of CA powers, including the Continental Shelf Act 1964 and Territorial Seas Act 1987.

9.3 Health and Safety

UCG at shallow depth using relative simple air injection techniques have previously been undertaken in the UK during the middle part of the last century. Changes in safety and environmental regulation mean that previous procedures are not applicable. UCG development proposed in the UK will involve accessing the in-situ coal at depth, (>500m) via boreholes drilled from the surface. The coal gasification process will be controlled through the use of steam and O₂ injection via an injection borehole with the gas produced brought to the surface via a production borehole. As this is a new concept no specific safety regulations are in place to address the needs of UCG although existing regulations should be capable of satisfying the overall process.

Drilling of UCG boreholes from the surface has been considered by HSE. While each application is viewed on an individual basis it is likely that any drilling activity would fall under the *Offshore Installation and Wells (Design and Construction, etc) Regulations 1996* and *Amendments to the Offshore Installations (Safety Case) Regulations 1992*. While no deep UCG boreholes have been drilled it is considered the drilling operation will be similar to that of a CBM well. There is experience in the UK of drilling CBM wells under the existing safety and environmental regulations.

The UCG process involves the injection of high pressure gases through pipes inserted in the injection well to maintain coal gasification. Surface equipment will be required to store, monitor, control and deliver these feeds together with a N supply to extinguish the coal burn if required. The gas produced by UCG is likely to be under pressure when it is brought to the surface via the production well.

Provisional inquiries to HSE indicate that depending on the quantities of dangerous substances, eg, O₂, or flammable gas stored on site such activities would be regulated

by *The Control of Major Accidents Hazards Regulations 1999* and associated regulations and guidance including the need to develop a safety report. Other regulations such as the *Pipelines Safety Regulations 1996* may be applicable.

While specific safety regulations are in place for surface drilling activities, consideration will need to be given to the extension of existing HSE guidance on surface gasifiers to the underground process.

The Construction Design and Management (CDM) regulations may not strictly apply to a UCG trial or operation but the owner would be strongly advised to adopt a similar framework as it represents good practice. Due to the interdisciplinary complexities, many of the sub-contractors, and the principal contractor, will not be familiar with all the processes taking place. A Planning Supervisor should therefore be appointed at an early stage in the design of a trial. One duty of the appointee would be to prepare a pre-tender health and safety plan to accompany tender invitations.

9.4 Environmental Regulations

UCG will need to meet Environmental Regulations and for on-shore applications is likely to fall under *The Pollution Prevention and Control (England and Wales) Regulations 2000*. Under PPC Regulations the system of Integrated Pollution Prevention Control (IPPC) is introduced. IPPC has the aim of achieving *a high level of protection of the environment taken as a whole by, in particular, preventing or, where that is not practicable, reducing emissions into the air, water and land* (Regulation 8 (2)- (3)).

A less than 50MW thermal input would exempt power generation from EA control under IPPC (Integrated Pollution and Prevention Control) and less than 20MW net rated thermal input would obviate the need for local authority control. In practice, commercial schemes are likely to fall outside these criteria.

However, gasification is a prescribed process and this would require permitting. IPPC becomes applicable in summer 2006. Currently, the Environment Protection Prescribed Processes Regulations 1991 apply which require authorisation from the EA to operate the gasification process.

Provided the power generation part of the scheme is exempt, energy efficiency is not an issue enabling a relatively simple, low cost turbine to be employed. Emissions from gas turbines are controllable using existing technology.

9.5 Gas Storage Standards

Whilst no specific guidance is available on UCG practices, guidance on the control of underground gas storage could provide an analogue to assist local authority planners and environmental regulators in deciding how to approach an application for planning consent. British Standard BS EN 1918:1998 Part 1 to 5 *The Gas Supply Systems – Underground Gas Storage* provides a useful overview of the critical elements which need to be considered. BS EN 1918 provides recommendations for the storage of gas in a number of settings including; aquifers, oil and gas fields, solution-mined salt

cavities, rock caverns and surface facilities specifying procedures, and practices, which are safe and environmentally acceptable.

Fundamental in the selection of an underground storage facility is a comprehensive assessment of the geological conditions. The assessment will require sufficient data is available to evaluate the geological characteristics to ensure satisfactory containment. The suitability of proposed facility is evaluated from a study of available data, geological survey, exploration, geophysical measurements, seismic and borehole drilling and logging.

The storage facility shall be designed to ensure the continuing long-term containment of the stored products. This presupposes:

- adequate prior knowledge of the geological formation in which the storage is to be developed and its geological environment
- acquisition of all relevant information needed for specifying parameter limits for construction and operation
- demonstration that the storage is capable of ensuring long term containment of the stored products through its hydraulic and mechanical integrity.

Design Principles

Surface and subsurface facilities should be designed to control the process at any combination of pressure and temperature, eg, the need for leakage protection and use of double containment principles should be considered. Proven technology should be used for analysis and calculations, with all data documented and emergency procedures developed.

Information required as part of the design of a storage facility will include; geological structure, horizontal and vertical strata characteristics, strata thickness, depth, faults, sealing properties of faults, permeability, porosity, capillary pressure of any cap rock and reservoir. Facilities can be designed so that there is sufficient depth to ensure hydraulic containment of the stored product.

10 RECOMMENDATIONS ON FUTURE R&D

10.1 Introduction

UCG R and D is aimed at developing technologies that will enable useful energy to be recovered from coal seams that are uneconomic to mine conventionally, in an economically viable way, with the minimum of damage to the environment. The type of technology and the level of sophistication required will depend largely on the size of the integrated gasification end-use scheme. In the past sophisticated technology has sometimes been developed only to discover that it does not provide financial benefits over existing, proven technologies. It is important, therefore, to involve potential operators and end-users early in the R&D programme.

The larger the scale of initial projects, the greater both the technical complexity and the risk to investors. Intermediate scale demonstration projects are one way of introducing and proving the technology pending full-scale commercial development. The speed of commercialisation can be accelerated if small or intermediate scale projects are shown to be financially feasible. Whereas a full-scale power station venture is likely to be a long-term goal, small-scale embedded power generation could be a medium-term opportunity.

UCG R&D requires substantial investment. The cost of UCG R&D to the UK could be reduced by seeking collaborative arrangements with other nations with similar, but not necessarily identical interests. Individual European countries, Australia, China and the USA could be approached. Development of the technology could also interest Canada which has, for example, near shore coal resources in Nova Scotia where underground mining has now ceased.

A suitable framework, which will allow commercial development to flourish, is as important as the technology itself. Government can assist commercialisation of UCG and encourage private involvement in its further development by:

- Continuing to support fundamental and applied research
- reducing regulatory hurdles and disincentives
- tax incentives for participants
- a favourable pricing mechanism for electricity generated using UCG
- recognising the benefits and needs for UCG in national energy, environmental and planning policy.

A further UCG trial should be undertaken to evaluate recent technological developments and to test aspects not completed in, or ideas generated by, the UGE trial in Spain. The EWG (1989) report proposed a second trial at greater depth than the Spanish trial. However, the premature termination of the former meant that the critical factor of cavity growth and its controllability using CRIP could not be evaluated. The actual depth of a second trial is therefore not of major importance provided it is reasonably representative of likely target depths in the UK.

The field trial programme should be complemented by laboratory and theoretical studies.

Field trials in the UK will provide lessons not only on technical but also on regulatory issues. The proposed site should be thoroughly explored before proceeding with the experiment. The requirements for process control and safety monitoring, particularly the ignition system, should be rigorously examined and suitable systems identified, or developed and tested.

10.2 A Drilling Trial

To design a full UCG trial without confirming the capability of the critical drilling technology could be too high a risk. However, a surface to in-seam drilling trial could be undertaken in conjunction with an alternative coal exploitation technology as a precursor to planning a UCG trial.

A previous report (Creedy et al 2001) has indicated the possible benefits of surface to in-seam drilling for virgin coalbed methane (VCBM) exploitation. The method could facilitate commercial gas production from lower permeability seams than have hitherto been achieved using fracking techniques in vertical wells. A guided drilling trial could be carried out as part of a CBM production and CO₂ sequestration field trial involving:

1. A surface to in-seam longhole drilled in a selected seam for a prescribed length (eg 400m) to intercept a vertical well and form a circuit.
2. Shutting off the vertical well to facilitate characterisation of gas production performance from the in-seam section.
3. Injection of a CO₂ rich gas mixture through the linked system to determine CO₂ removal rate and ECBM. The results could be compared with the 'huff and puff' (cycle of injecting CO₂, soaking then producing gas) approach being tested in Canada.

The aim of a drilling trial would be to confirm the applicability of the technology to UK conditions. Although technology driven, the success will also depend on the effectiveness of the planning and management of the exercise.

10.3 UCG Field Trial

A future UCG trial should:

- Be undertaken at a geologically and hydro-geologically suitable site capable of supporting up to a 10 year experimental programme;
- Prove the technical feasibility at a depth in the range 600m to 1000m;
- Operate two gasifiers to completion, one after the other, and include a detailed post-burn investigation of the cavity development;
- Include environmental monitoring (gas and liquids) wells in selected strata above the gasification zone;
- Investigate whether can 'stop and start' gasification solely by controlling O₂ flows (ie turndown);
- Include a small-scale power generation system to demonstrate the usability of the product, and to facilitate further research on corrosion control and turbine efficiency;
- Study subsidence affects and assess whether current mining-based methods are adequate for predicting worst case expectations;
- Include a detailed financial appraisal;
- Provision for adequate funding, including contingency to deal with unforeseen technical problems. A detailed costing is needed, but initial estimates suggest a sum of £15 million to £20 million may be needed to construct, successively operate and study two linear gasifiers, including an 8MW_e generator. A guided drilling trial alone, involving linking two wells at 800m depth with 400m in-seam could cost around £2 million.

The Requirements of a UCG Trial Site

Whereas planning difficulties could be relatively easily overcome by undertaking an offshore experiment, the added costs and new engineering problems to be tackled could prevent the identified objectives being satisfactorily addressed. An onshore site would therefore be preferable for the next stage of research and development although a near-offshore target might be worth considering.

Factors to be considered when choosing a trial site include:

- Planning issues (proximity of neighbours, environmental sensitivity, need, life of site)
- Geology (seam depths, seam thicknesses, dip, coal rank, nature of roof and floor strata)
- Hydrogeology (positions of aquifers, inflow risk and flow potential)
- Mining (distance from any recorded and possible unrecorded workings)
- Gas use (proximity to small-scale industrial user or suitable electrical grid connection)

A preferred UCG site would involve development of a gasifier in Coal Measure strata. The target seam should ideally consist of at least 2m of non friable, fault-free coal with a weak roof to encourage caving and possibly a relatively strong floor to assist drilling guidance. Results from longwall mining research can be used to estimate possible heights of disturbance zones for various gasifier geometry's. No significant aquifers should be present within the expected zone of disturbance. There should be no mining activities, current or planned, near the trial site.

Coal Seam Dip

UCG trials have been undertaken in shallow steeply dipping strata in the USA in Rawlins, Wyoming from 1979 to 1981 building on a concept first developed by the Russians. The reactor geometry offers advantages in terms of process control presumably due to the natural migration of the gasification zone up dip.

There is a generally held belief that even for deep gasification the target seam should be dipping (but not steeply, say $<30^\circ$).

A possible advantages of the production well lying up-dip of the injection well could be that any strata water makes flow towards the reaction zone to form the steam component, rather than simply to increase the moisture content of the product gases, assuming there was no risk of significant inflow.

Conversely, at the Spanish trial site, a dip of 30° towards the production well meant that higher than expected water inflows migrated to the production well, mostly by-passing the reaction zone. The water was produced and separated at the surface without excessive detriment to the gasification process. Without significant dip at the Spanish trial site, the process would probably have been quenched.

De-watering on completion of in-seam drilling is also assisted by strata dip. The pressure and thermal gradients produced during gasification may overwhelm any gravitational effects so the process itself may not be significantly affected by dip.

Deep gasifiers in bituminous coals in the UK are likely to meet dry conditions in most instances. Provided casing which penetrates shallow aquifers is properly cemented in place, sites can be selected where the risk of water incursion is very low.

The amount of seam dip may not, therefore, be a critical factor. Nevertheless, when designing a layout, consideration should be given to the orientation of the gasifier with regard to dip to control water and any low-volatile liquid gasification products.

10.4 Drilling Issues

Choice of Drilling Technology

The two principal drilling tools are down-hole motor with bent sub and steerable rotary systems although hybrid arrangements are used in some instances. Together with MED technology either of those systems should be capable of completing an injection well in a deep coal seam. A geophysical location device in the target well may help to increase the accuracy of interception to form the gasification circuit.

The selection of technology should be a matter for the drilling contractor and will depend on the performance specification required.

Selection of a Drilling Contractor

The drilling result obtained will not only depend on the technology used, solution of appropriate equipment and site geological factors, but also on the management, technical skills and experience of the drilling design and operational teams.

The surface to in-seam coal drilling specialists tend to be relatively small companies operating out of the USA and Australia, but they appear keen to apply their technology overseas. Within the UK there is considerable experience of oil and gas guided drilling gained from offshore oil and gas exploration and production. Sophisticated equipment, international company support and substantial backup services are available.

For commercial development of UCG it is desirable to have a choice of drilling contractors and there may be cost and service benefits from using established UK contractors.

At the R&D stage, the knowledge and experience of the drilling contractor should be taken into account when designing a drilling programme. The technology and equipment should be selected by the contractor based on the performance specification to be achieved in the contract. A risk-sharing contract could be developed to assist in supplying the necessary incentive. At the tender evaluation stage, short-listed contractors should be asked to present their methodology in detail.

The choice between coal and oil and gas drilling services is not easily made. The oil and gas specialists have the tools for linking wells, coal specialists have the experience of longhole drilling in coal.

10.5 Fundamental and other Research

Academic and contract research organisations can additionally complement the field trials through:

- A study of the dispersion of gases and liquids in the strata surrounding a cavity using analogues of similar processes, mathematical modelling and post-closure investigation of an exhausted gasifier at the site of the proposed UK trial
- Development of a water inflow model to predict expected water influx into the cavity. Its contribution to the gasification process as a reactant and its retarding effect as a coolant should also be examined
- Refinement of a cavity growth model, to allow CRIP simulations, and links to the water inflow model. Geotechnical and thermal stress factors should be considered. The numerical model should be capable of predicting likely subsidence profiles at the surface resulting from both single and multi-seam gasification
- Use of CFD techniques to review effects of cavity shape, geometry and strata dip on flow processes in the reactor
- Laboratory studies to establish tests suitable for evaluating the likely gasification and pyrolysis performance of coals of different composition and rank. The possibility of testing confined coal samples under conditions of high pressure and temperature to simulate deep UCG processes could also be investigated
- Laboratory investigation on the effect of thermal stress on typical seam roof rocks. should be experimentally investigated in the laboratory
- A seam characterisation method for assessing drillability, possibly involving measurements and laboratory testing on cored samples
- A quantitative appraisal of potential UCG resources in the UK – onshore, offshore and near-shore.

Validated models could prove invaluable for feasibility appraisals, environmental impact assessments and process design. The numerical models are likely to be complex and therefore general rules should be derived and used to produce simplified empirical, practical models for operators to use.

11. CONCLUSIONS

UCG is potentially the most important clean coal technology of the future with worldwide application. Ultimately, it could be a substitute for deep mining coal for power generation use.

Experience at El Tremedal indicates the following are likely to be important technical requirements and considerations in designing a commercial gas production scheme:

- A cost-effective means of acquiring high-resolution coal seam geological data

- Reproducible drilling accuracy
- Multiple, independent gasifier units (with separate injection and production wells) to ensure systems failures do not totally halt gas production
- Integrated surface plant using readily available off-the-shelf equipment wherever practicable.

The most critical element of deep UCG is arguably the directional drilling. Technologies exist which are capable of achieving the required precision but there is considerable uncertainty about the general drillability of coal seams in other than ideal conditions.

Due to a lack of experimental data, insufficient is known about gasifier growth and geometry to fully assess commercial feasibility. A preliminary financial evaluation indicates that a 50MW_e scale integrated UCG power generation project may be viable and this scale may be attractive to the embedded generation industry. A developer investor could minimise business risk by installing a natural gas supply to the generator to ensure electricity supply commitments can be met and cash flow from revenue maintained.

More sophisticated well layouts than simple well pairs could be designed, but an increased level of complexity is not warranted at the present stage of experimentation.

The UK's Cleaner Coal Technology Programme identifies the following UCG technology targets (Energy Paper 67, Summary, April 1999):

1. Improved accuracy of in-seam drilling to achieve on a consistent basis, a 400m borehole in a 2m thick seam.
2. Assessment of the implications of burning the gasifier products in a gas turbine.
3. Estimates of the landward resources of coal technically potentially suitable for UCG (initially seams 2m at depths ≤ 1200 m).
4. Identification of a site for a semi-commercial UCG trial.
5. UCG performance needed to compete with North Sea gas.
6. Pre-feasibility of offshore exploitation of UCG in the southern North Sea.

Information provided in this report indicates that drilling technology has progressed to a level capable of achieving item 1, subject to geological conditions. Research is in progress to improve the performance and reliability of gas turbines using aggressive fuel gas (Alstom, 2001) such as that produced in a surface gasifier. A preliminary examination has been made of potential UCG resources onshore and offshore UK. Site selection criteria have been considered in this report but site identification is outside the scope. A financial analysis has been undertaken using detailed cost data and a simple gasifier model which indicates competitiveness of UCG product gas for power generation. A pre-feasibility study of offshore exploitation has yet to be undertaken, although a start has been made gathering financial data to develop a cost model.

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Table 1: Comparisons of CO₂ emissions (adapted from Green 1999)

Fuel	Utilisation process	Efficiency %	CO ₂ t MWh ⁻¹
UCG gas	Modern steam plant	38	1.00 to 1.14
UCG gas	Combined cycle	46	0.83 to 0.94
UCG gas CO ₂ removal	Combined cycle	46	0.44
	IGCC	46	0.43
Natural gas	Modern steam plant	38	0.93
Coal (pulverised fuel)			

Table 2: Chronology of the El Tremedal trial

Date	Activity
1988	Six member states of the EU form a European Working Group (EWG) to propose a UCG development programme
April 1989	EWG propose a trial to the EC
1990/91	Country and site selection
1991/92	Participant and EU project approval, legal and contract negotiations
1992/93	Site preparation and exploratory phases
October 1993	Drilling of the injection well commences
December 1993	Drilling of the production well starts
July 1997	First ignition close to the base of the production well (9 days gasification).
October 1997	Two further ignitions, 4 days gasification after the first and termination of the experiment after the second due to damage caused by a violent ignition
June to July 1998	Post gasification investigations undertaken.
September 1998	Wells abandoned and sealed
December 1998	Surface plant dismantled.

Table 3: Comparisons of principal guided drilling technologies

Rotary steerable	DHM with bent sub
Advantages	Advantages
<ul style="list-style-type: none"> • Increased drilling rates resulting in quicker completion time • Greater accuracy of borehole trajectory • Can be used in thinner target horizon • Cleaner hole completion with smoother borehole profile assisting casing installation 	<ul style="list-style-type: none"> • Proven robust technology • Widely used • Availability of equipment and operators with coal experience • Cheaper than rotary steerable to mobilise
Disadvantages	Disadvantages
<ul style="list-style-type: none"> • Lack of operators with specific coal experience • Can be costly to mobilise • Limited build up angle compared with bent sub unit 	<ul style="list-style-type: none"> • May produce a stepped hole finish which impedes casing installation • Slower response time to change borehole direction • Requires withdrawal of drill rods to change bent sub angle

Table 4: Principal cost items, 800m depth, 400m gasifier

Cost item	8MW_e Model (£million)	50MW_e Model (£million)
Drilling (10yrs)	14.3	83.4
Gas turbine package	6.0	25
Process equipment, gas cleaning, monitoring and control systems, ancillary installations etc	4.7	16.6
Total capital requirements	25.0	125

Table 5: Electricity production costs for an integrated 8MW_e scheme, 800m depth gasifier (assuming 80% gasification efficiency, 95% availability, 32.5% turbine efficiency)

Gasifier length (m)	Mean gasifier width (m)	Production cost p kWh ⁻¹ (before tax and interest)	
		11MJ m ⁻³ (LHV)	15MJ m ⁻³ (LHV)
400	40	5.27	4.33
400	100	4.00	3.25
400	200	3.58	2.78
600	60	4.30	3.33
600	125	3.62	2.82
600	300	3.39	2.65

Table 6: Electricity production costs for an integrated 50MW_e scheme, 800m depth gasifier (assuming 80% gasification efficiency, 95% availability, 32.5% turbine efficiency)

Gasifier length (m)	Mean gasifier width (m)	Production cost p kWh ⁻¹ (before tax and interest)	
		11MJ m ⁻³ (LHV)	15MJ m ⁻³ (LHV)
400	40	3.25	2.91
400	100	2.07	1.72
400	200	1.66	1.32
600	60	2.21	1.89
600	125	1.73	1.38
600	300	1.48	1.14

Table 7: Electricity production costs for an integrated 50MW_e scheme, 800m depth gasifier (assuming 80% gasification efficiency, 95% availability, 41.6% turbine efficiency)

Gasifier length (m)	Mean gasifier width (m)	Production cost p kWh ⁻¹ (before tax and interest)	
		11MJ m ⁻³ (LHV)	15MJ m ⁻³ (LHV)
400	40	2.70	2.38
400	100	1.77	1.45
400	200	1.45	1.14
600	60	1.88	1.59
600	125	1.51	1.19
600	300	1.31	1.00

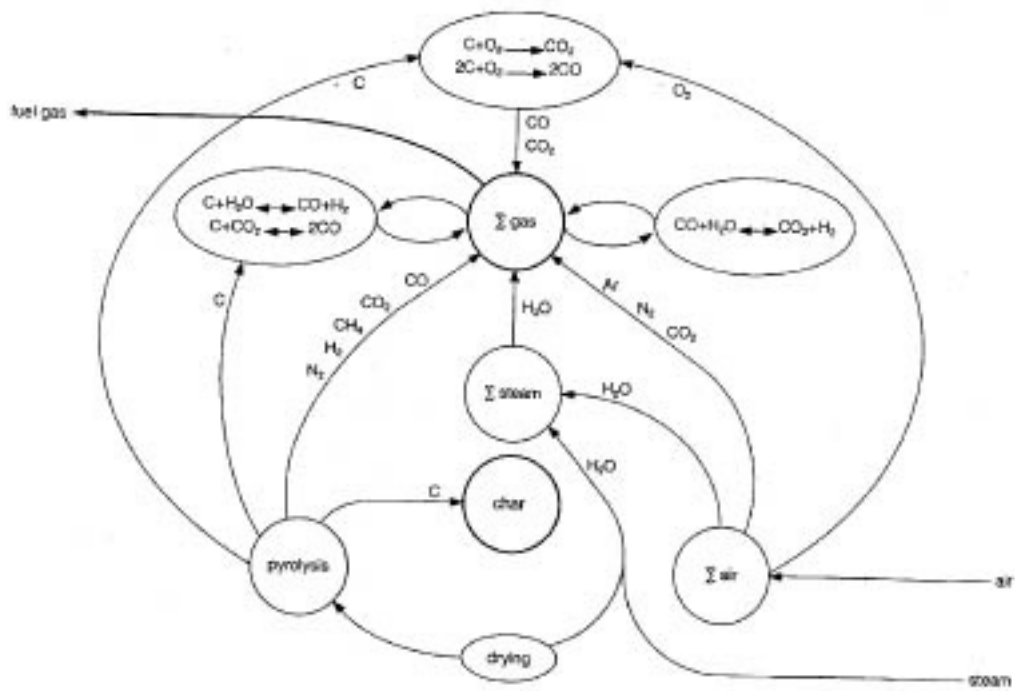


Figure 1: Chemical reaction pathways during underground coal gasification (adapted from Donne and others, 1998)

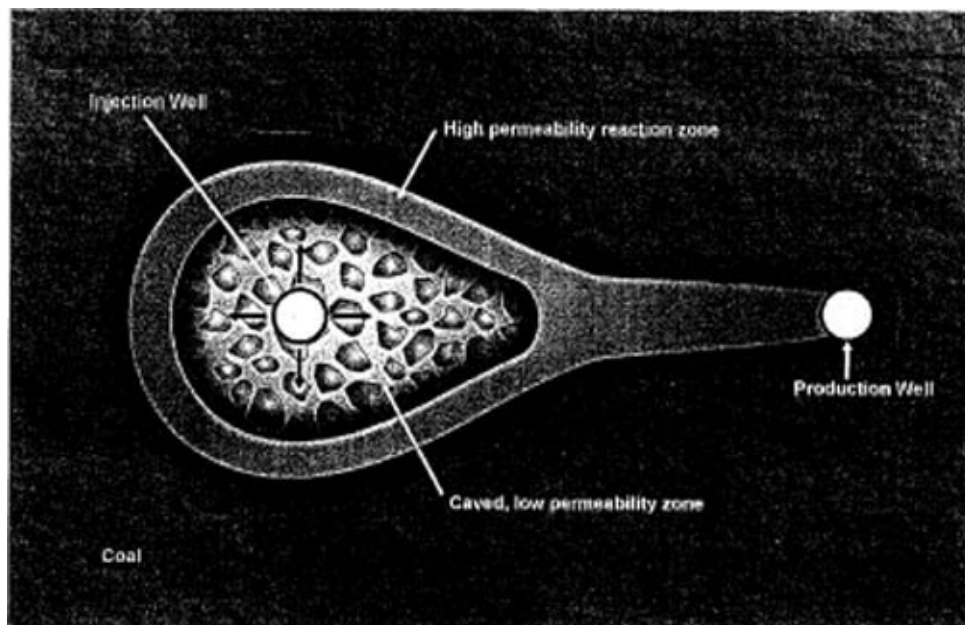


Figure 2: Gasification model after Wilks (1963)

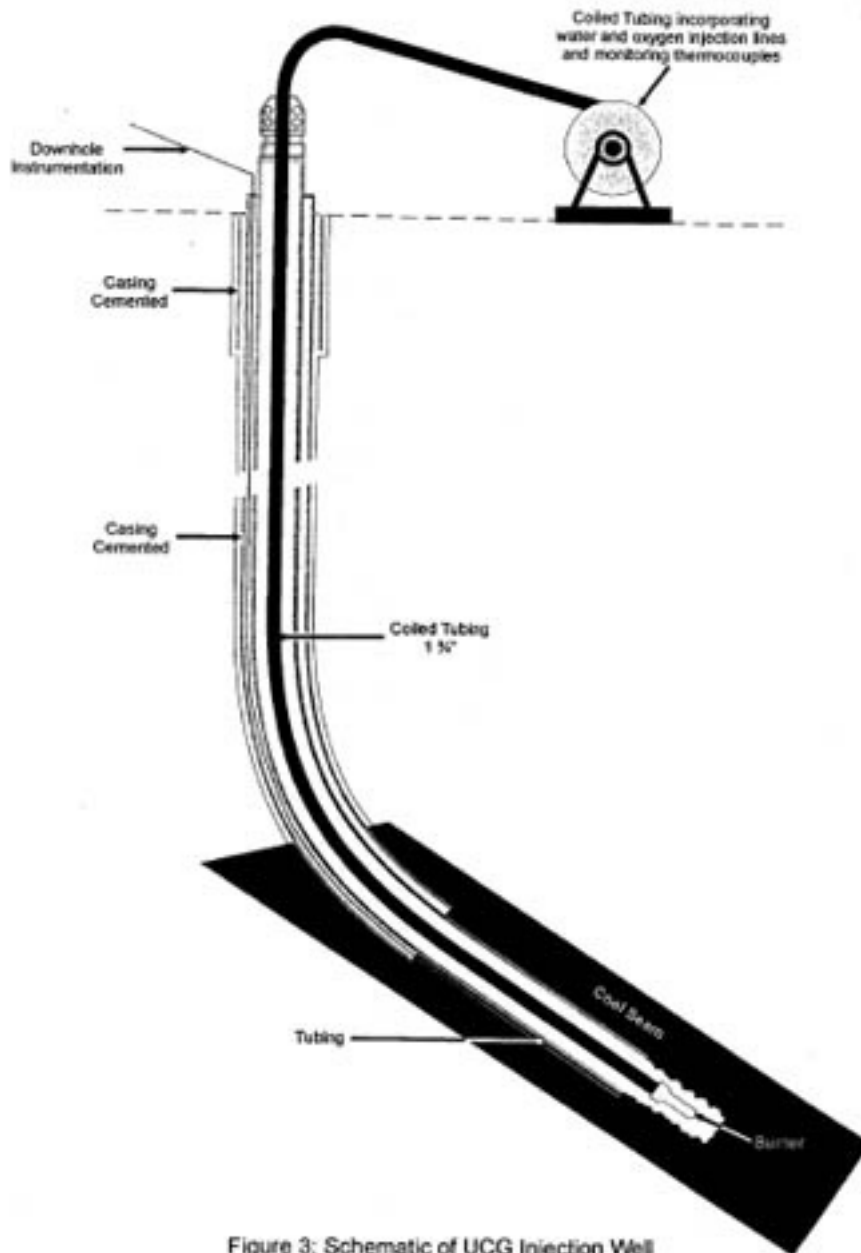


Figure 3: Schematic of UCG Injection Well