Introduction

Underground coal gasification (UCG) is the conversion of coal in the seam into a combustible gas. The UCG gas can be used for electricity generation as well as hydrogen production or conversion into liquid fuel and chemical feedstock. The energy is recovered directly from coal seams, avoiding mining-related hazards and the handling of surface coal and post-combustion ash. The main technical challenges arise from issues such as the need to protect underground aquifers requiring the assessment of environmental risk, and the planning. In this respect, legislative and public perception issues are likely to arise in any planning application.

This report assesses the feasibility of UCG in the UK based on the findings of the Coal Authority’s and the DTI’s UCG investigations. As part of this review, a series of studies have been performed covering resource, technical, environmental, planning and public perception issues and the economic viability of this technology. This report presents the key findings and makes recommendations on the future treatment of UCG.

During the period of this study, the Government published the Energy White Paper, February 2003 ‘Our energy future - creating a low carbon economy’ which, attached importance to the use of CO₂ capture and storage (CCS) technologies with fossil fuel combustion. This changed significantly the context in which UCG can be considered as a future energy option.

History of UCG

There is a long history of UCG development in the UK. Experiments were undertaken in Durham in the 1920s. In the 1950s, trials were done at Newman Spinney in Derbyshire and Bayton in Worcestershire. These trials succeeded in the gasification of significant tonnages of coal and enabled valuable operating experience to be gained. The decision to abandon UCG by the National Coal Board was taken on economic grounds in the late 1950s with the ready availability of cheap oil. Elsewhere, UCG was also being pursued, particularly in the former Soviet Union, where several large-scale schemes were developed. In addition, an extensive US field trial programme was undertaken in the 1980s. However, interest began to wane with the availability of low-cost natural gas and the environmental concerns associated with operating UCG at shallow depth.

In the 1990s the European Union supported a project proposed by Belgium, Spain and the UK on the gasification of deeper coal seams. The work constituted a UCG trial carried out at a depth of 550m in the El Tremedal coalfield of eastern Spain (1992-1998) and clearly demonstrated that, using the latest drilling and injection control technology, UCG in deeper coal seams would be technically feasible. As the results of the Spanish trial were promising, UK opportunities for UCG featured in DTI Energy Paper 67 (1999) which encouraged this review. The extensive overseas activities that have taken place during the period of this study in Australia, China and elsewhere have been taken into account in the development of this report.

Figure 1.1 UCG, test site at Newman Spinney (c.1955)
Environmental Perspective

It is now acknowledged that climate change is occurring, and that the natural ‘greenhouse effect’ is enhanced by a build-up of greenhouse gases, mainly CO₂ from combustion of fossil fuels. Assessments by the Intergovernmental Panel on Climate Change (IPCC) suggest that the global average surface temperature increased by about 0.6°C over the 20th century and is projected to rise further. To prevent the most damaging effects of climate change, the EU suggested in 1997 that we should aim for a temperature increase of no more than 2°C above the pre-industrial level, equivalent to keeping the concentration below about 550ppm, or about twice the pre-industrial level. The present level is about 375ppm. To stabilise CO₂ at or below this level over the next 100 years would require a global emissions reduction relative to the ‘business as usual’ trend of 50 to 60% by 2050 and 70 to 90% by 2100. The UK Government in its recent Energy White Paper¹ supports this view and has committed itself to a 60% reduction in CO₂ emissions by 2050.

These are challenging targets as global energy demand is increasing and fossil fuels will be a major component of the energy mix for decades to come. It is essential, therefore, that ways are found to increase the efficiency of fossil fuel use and to move towards low and eventually zero emission supply technologies. The latter goals will necessitate, amongst other measures, the successful development and implementation of low to zero carbon abatement technologies.

The Potential of UCG

UCG provides a route to achieve the goal of reduced CO₂ emissions as the technology easily lends itself to CO₂ capture, both from the raw UG gas and from subsequent downstream processing/utilisation. UCG, therefore, has the potential to be a relatively low carbon emission technology, provided that the CO₂ captured in the processing can be satisfactorily transported and sequestered. This raises issues about safety and environmental impact, with the associated need for monitoring and verification procedures being addressed in other work² on CCS by the DTI. It has been assumed that the anticipated developments for fossil fuels (i.e. CO₂ pipeline networks, saline aquifers, enhanced oil recovery (EOR), etc) will be available over the timescale of commercial development of UCG (15 years+) and suitable solutions will be available to sequester the CO₂ from UCG large-scale processes.

On a global scale, coal will be a component of energy supply for power generation well into the foreseeable future and its use is increasingly significant in many developing countries. Continued use of coal by deploying cleaner coal technologies can help the environmental and security of energy supply issues, and the use of indigenous coal may provide price stability against imported coal. To quote the Energy White Paper, “In a low-carbon economy the future for coal must lie in cleaner coal technologies – which can increase the efficiency of coal-fired power stations and thereby reduce the amount of carbon they produce – or carbon capture and storage”.

UCG is one of a suite of coal technologies which could provide a combination of high generating efficiency and a potentially satisfactory method for CCS. The evidence to date suggests that UCG compares well with, for example, Integrated Gasification Combined Cycle (IGCC) and supercritical thermal plant. UCG, however, is less advanced than either of these technologies and questions specific to UCG, such as planning approval, environmental impact and operation at commercial scale, still need to be tested in a full-scale trial (costing £10-£20 million) before commercial decisions can be taken. The costs and developmental risks in

¹ Energy White Paper, Our energy future – creating a low carbon economy, DTI, February 2003
² Review of the feasibility of carbon dioxide capture and storage in the UK, DTI Report, DTI/Pub URN 03/1261
evaluating the technology need to be balanced against the benefits.

Some criteria by which UCG needs to be judged are as follows:

1. The commercial viability of UCG compared with other sustainable fossil fuels likely to be commercial within the next 15 years.

2. Local and global environmental impacts of UCG compared with competing fossil fuel and other technologies.

3. The likely cost and risks of developing UCG-CCS technologies through to commercialisation, and the scope for industrial support and overseas collaboration.

4. The competitive position of UK technology in UCG compared with overseas developments.
2. Technology Status of UCG

Basic Underground Processes

UCG is a process in which underground coal in the seam reacts with oxygen (or air) and steam to produce a combustible gas of low/medium calorific value. The process is similar, although not identical, to the surface gasification of coal at the heart of IGCC. UCG is basically a coal to gas conversion process, like IGCC and town gas production.

UCG is conceptually very simple, but controlling the reaction and producing a consistent gas quality under a variety of geological and coal conditions have been difficult to achieve. The basic concept, see Figure 2.1, has two boreholes, one for the injection of oxidants and the other for the removal of the product gas. The oxidants react with the coal in a set of gasification and pyrolysis reactions to form carbon monoxide, hydrogen, methane, carbon dioxide and a variety of minor constituents.

Transport of the gases between the inlet and outlet boreholes controls the reaction. Coal can vary considerably in its resistance to flow, even in the same coal seam. Younger coal such as lignite may have sufficient permeability to enable a satisfactory connection between wells to be created over short distances (20-50m), but most other coals are too compact or variable to rely on the natural fissures as pathways for UCG.

UCG development has largely been concerned with enhancing the connection between boreholes in coal, controlling the underground process, and scaling up the process to commercial-sized operations. These are not trivial problems, and are hampered by the fact that, generally, tests can only be made at full-scale in real coal seams, trials are expensive and the results are often difficult to assess at the depths and conditions of UCG.

The mid-1990s onward has seen a resurgence of interest in UCG throughout the coal-producing world, and recent trials have established that viable solutions to the seam connection problem can be achieved. In summary, three methods of UCG have now evolved.

The first method, based on technology from the former Soviet Union, relies on vertical wells coupled generally with air pressurisation to open up an internal pathway in the coal. The process has been tested recently (1999-2003) in the high-ash coals at Chinchilla, Australia. It was reported at the recent DTI Workshop on UCG that commercial feasibility studies are underway in India, Pakistan, Canada and Australia, and there may also be some interest in this method in the UK.

The second (Chinese) method uses man-built galleries in the coal seam as the gasification channels, and boreholes are constructed to communicate with the surface. The process operates on alternating air and steam and 11 field trials have been started since 1986; the Chinese UCG programme is the most extensive in the world.

UCG International Workshop, DTI Conference Centre, October 2003 (presentations available on CD and DTI website)

Figure 2.1 Basic configuration for UCG
The third method, tested in European and American coal seams, is to create dedicated inseam boreholes, using drilling and completion technology adapted from oil and gas production, see Figure 2.4 and Appendix 1 for details. It has a moveable injection point known as CRIP (described in the following section) and uses oxygen, rather than air, for gasification.

The UK, as one of three participant countries in the recent European trial in Spain (1992-1998), has developed knowledge of inseam drilling (method 3), whereas data available on Chinchilla and the Chinese trials are limited. Each method involves some proprietary techniques, which have not been disclosed.

UCG trials and commercial operations outside Europe have all taken place in relatively shallow coal seams, see Figure 2.2, whereas recent European trials have generally been deeper. Shallow operations have lower drilling costs but the disadvantage is the potential for environmental pollution. The two recent European trials in Belgium and Spain at coal seam depths of 840m and 550m respectively, showed that operating at high pressure (>50bar) favours the formation of methane, thereby improving the calorific value of the product gas. There is also evidence that wider cavities are produced as the depth of the coal seam increases.

The current DTI programme on UCG was initiated on the assumption that inseam drilling offers the best prospect for accessing and constructing UCG wells in the deeper and relatively impermeable target seams of the UK. The establishment of these criteria does not rule out UCG projects in shallow UK seams, if local site-specific factors support it - see environmental chapter below.

**Relevant Technical Issues**

The underground part of UCG requires a multi-disciplinary understanding of geology, hydrogeology, mining, drilling and exploration and the chemistry and thermodynamics of the gasification reactions in the cavity. Interaction between disciplines is essential and some of the key technical issues are:

**Exploration**

Any potential site for UCG operations will need to be explored with a combination of well-spaced boreholes, seismic surveys (preferably three dimensional) and the use of a software package to correlate the exploratory data. The programme will be designed to identify geological structure at coal seam depth to a resolution of at least coal seam thickness, and over an area of coal sufficient to meet the project lifetime objectives (trial, semi-commercial or large-scale operations). Coal reserve margins will need to be built in to allow for geological and planning uncertainties.

A thorough understanding of the coal seam characteristics is a pre-requisite for the design and construction of UCG process wells. It is also important to have good knowledge of the adjacent strata to ensure well bore and environmental integrity, and provide the necessary information for the environmental impact assessment (EIA),

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*3D seismic surveys use multiple linear arrays of geophones at right angles to the line of seismic sources. Resolutions to 2m are achievable in good conditions, compared with ~5m for conventional 2D seismic.*

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*Figure 2.2 UCG trial projects with depth (1947-2002)*
almost certainly required for a UK planning application.

Exploration presents no exceptional technical problems for UCG operations, although there is always the risk that sites could be rejected as evaluation unfolds. The costs of exploratory drilling and a 3D seismic survey are high, but generally necessary for successful inseam drilling operations.

Directional Drilling in Coal

The construction of the wells, the inseam trajectory and the borehole intersections requires considerable accuracy, and would have been beyond the capabilities of drilling technology just a few years ago. Attempts to develop steerable drilling equipment by British Coal and others in the 1980s made slow progress but, more recently, the oil and gas industry has developed steerable long-reach drilling (up to 15km in some cases) to extend reservoir exploration and production. The major service companies responded with a variety of steerable technologies, on-line logging equipment and sophisticated telemetry to communicate with the surface.

Directional drilling in coal, as explained in more detail in Appendix 1, is a lower cost operation, compared with oil and gas. The basic steerable downhole motor has to be adapted for coal, and additional sensors are required to track the coal seam boundary and control the fluid pressure at the bit. A worldwide review of directional drilling in coal has identified a small number of specialist contractors with lateral seam drilling experience, and it is recommended that these be used in any early UCG trial. This technology is now reasonably well proven overseas for coal bed methane (CBM) (in the USA) and coal exploration (in Australia and South Africa). Although inseam process wells were successfully constructed in the Spanish UCG trial, application of these newer coal-drilling techniques to UCG still has to be fully demonstrated.

CRIP (Controlled Retractable Injection Procedure)

Previous UCG trials have shown that a cavity develops and grows with a characteristic shape in the direction of flow, Figure 2.3. Eventually, as the cavity becomes large, gas quality decreases, and the channel is no longer effective: therefore, vertical wells, if used without inseam drilling, have to be close together. This problem was overcome in the later UCG trials by controlling the position at which oxidants are injected into the coal seam, and moving the injection to new coal when required, using a device and manoeuvre known as CRIP, as shown in Figure 2.4.

Further details of directional drilling and CRIP are given in Appendix 1.

UK Coal Resources for UCG

The UK coal resources, including those offshore, are probably the largest in Western Europe and it is estimated that only 1-2% has been mined since the Industrial Revolution. Apart from the lignite deposits in Northern Ireland, Devon and
under the North Sea, most of the coal is bituminous in multi-seam deposits from outcrop to well over 2000m depth. Further exploitation of this vast indigenous resource by conventional mining, beyond the current activity, is very unlikely for economic and social reasons.

A study was initiated by the DTI (2001) to examine the suitability of onshore UK coals for the new technologies of UCG, CBM and CO₂ sequestration on unmineable coal. It was based on the extensive borehole and other data of UK coalfields, now held in digital form at the British Geological Survey. The selection criteria for a satisfactory UCG area were as follows:

- Coal seam >2m thick.
- Depth between 600 and 1200m.
- The availability of good density borehole data.
- Stand-off of >500m from abandoned mine workings, licensed areas.
- >100m vertical separation from major aquifers.

For this generic study, a minimum depth of 600m has been assumed to lessen the environmental impact at surface in terms of...
hydrogeology, subsidence and gas escape. This does not rule out shallow UCG in the UK for specific sites, where the local strata and hydrogeological conditions can support a shallower operation. The 1200m depth represents the normal limit for mining in the UK, and the same figure was used for UCG on the basis of drilling costs and working pressure at surface. More work might establish that UCG can go deeper, and there are advantages in terms of energy produced in doing so. These criteria could be refined for specific sites depending on geological and hydrogeological conditions. Coal characteristics are considered secondary factors for the type of UCG under consideration, i.e. high pressure and oxygen-based.

A set of 40 maps of the UK coalfields is now available on CD-ROM and the key areas are shown in Figure 2.5. Resource

![Figure 2.5 Principal UK resource areas for UCG](image)
calculations indicate that 17 billion tonnes of coal, i.e. nearly 300 years’ supply at current levels of coal consumption, are potentially suitable for UCG. The largest areas are in Yorkshire, Lincolnshire, Warwickshire and the Dee area with smaller coal deposits in South Wales and the Clackmannan Coalfield in Scotland. The Firth of Forth and the banks of the Dee Estuary are particularly attractive because of their proximity to existing industrial sites.

The favourable UCG areas identified in this study would need to be followed up with more detailed investigation of the geology and hydrogeology of the target area. The study also needs to take into account the surface environmental and planning issues, discussed in Chapter 3.

**Gas Utilisation in Surface Plant Gas Processing**

A UCG site will be concerned with handling large volumes of toxic and high-pressure gas, which has to be washed, cooled and filtered before transmission by insulated pipeline to the power-generating site. Purge gas storage will also be required. Locating the equipment at the surface UCG station and protecting the local environment from gas escape, equipment failure emergency procedures, blow-offs and spillages will be a significant environmental challenge for the operators.

The essential surface connections, and plant for a commercial UCG power generation scheme, are shown in Figure 2.6.

Plant is required to:

- Prepare, compress and inject the gasification agents into the injection well.
- Clean-up the gases for power generation.
- Optionally to steam reform, shift and remove CO₂ from the pre-combustion stream.
- Provide power generation using Combined Cycle Gas Turbine (or possible boiler and steam turbine).

*Figure 2.6  Schematic of UCG for power generation*
Typical size and output characteristics for two UCG plants of 50MWe and 300MWe capacity are shown in Table 2.1.

<table>
<thead>
<tr>
<th></th>
<th>50MWe</th>
<th>300MWe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total electricity produced/year</td>
<td>350GWh</td>
<td>2,100GWh</td>
</tr>
<tr>
<td>Number of coal seam panels (500m x 500m) required for 20 years’ operation</td>
<td>6.6 panels</td>
<td>24 panels</td>
</tr>
<tr>
<td>Equivalent tonnage of coal in ground required for 20 years’ operation</td>
<td>5.4 million tonnes</td>
<td>19.5 million tonnes</td>
</tr>
<tr>
<td>Maximum daily oxygen requirements</td>
<td>416 tonnes/day</td>
<td>1,792 tonnes/day</td>
</tr>
<tr>
<td>CO₂ captured/year</td>
<td>320,000 tonnes/year</td>
<td>1,380,000 tonnes/year</td>
</tr>
</tbody>
</table>

The production of oxygen, removal of CO₂ and other acid gases, and the utilisation of gas for power generation are mature technologies from the power and chemical industries which require little or no development. A wide choice of equipment is available for each section of the plant and a design process should consider the options, costs and regulations in detail to arrive at an optimal solution for any particular application. Some general points about the plant are as follows.

### Oxygen Supply

Oxygen for the gasification process can be supplied as air, enriched air or oxygen. The Chinchilla, Australia and Chinese programmes use air to produce a dry gas of calorific value 3-5MJ/m³, whereas the Spanish trial on pure oxygen at high pressure achieved over 13MJ/m³ after gas clean-up. Oxygen production has a high demand for energy, but the compensations are improved gasification stability, better cavity growth and an 80% reduction in the volume of injection gases that need to be compressed.

Oxygen supply will be required for any high-pressure UCG application for reasons of cavity growth and pre-combustion CO₂ capture. The table above indicates that a 300MWWe UCG project will need an oxygen supply of 1,800 tonnes/day – this indicates that a dedicated air separation unit (ASU) would be required. For the smaller 50MWWe plant, a pipeline supply, the use of road tankers or a membrane separation unit might be considered as alternatives to the ASU.

### Clean-up of Gases

The product gas, in addition to the combustible gases carbon monoxide, hydrogen and methane, contains carbon dioxide, water vapour, various minor intermediate products and tars, heavy metals, reduced sulphur, possibly chlorine and nitrogen compounds and some carry-over solids. A typical dry gas composition for oxygen-fired product gas (extrapolated from the Spanish UCG trial) after removal of any hydrogen sulphide is shown in Figure 2.7.

It should be noted that UCG product gas has a similar calorific value to surface gasification, because of the high methane content. In addition, pressure energy is available at the surface from the high operating conditions of the underground process (60-120 bar).

![Figure 2.7 Composition of typical dry UCG product (oxygen-fired) after gas clean-up (calorific value 13.6MJ/Nm³)](image-url)
The dry gas, which emerges from the cleaning process discussed above, can be combusted directly or it can be pre-processed to remove part or all of the carbon gases. CO₂ capture options are discussed in Chapter 3.

The gases leave the wellhead at elevated temperature and pressure, which for UCG on oxygen firing could be as high as 200°C and 100 bar at the production wellhead. A basic scheme for clean-up and treatment, which is similar to surface gasification, is shown in Figure 2.8.

The high pressure of the product gas from deep UCG implies lower gas volumes and smaller gas processing plant than conventional IGCC: also, the excess pressure can be converted (by turbine expansion) into electrical power for general plant use including providing power for the ASU. The greater the depth that the UCG process takes place, the greater the availability of pressure energy for power at the surface. This is an important advantage of UCG in deep coal seams.

The combination of the washing process and cyclone will remove most of the minor contaminants, leaving acid gases such as H₂S to be extracted by physical or chemical absorption using organic solvent such as amine or glycol. An advantage of gasification processes, such as UCG and IGCC, is that sulphur (and mercury) can be removed more efficiently and cheaper in the pre-combustion stream compared with post-combustion processes.

These clean-up processes themselves produce liquid effluent streams, which need to be regenerated and cleaned before discharge, or transported away for treatment. The Chinchilla UCG project⁵ makes a virtue of the waste streams by suggesting that the tars, oils and phenols are separated and sold as a by-product of the UCG process.

**Power Generation**

Electrical power can be produced from UCG product gas by turbine, reciprocating gas engine or simply burning the gas in a thermal power plant. The use of UCG product gas in engines and thermal plant has been demonstrated, but the performance of UCG gas in gas turbines is based on the extrapolation data for other low to medium CV gases.

⁵ See worldwide review of UCG later in this chapter
Turbine manufacturers have adapted gas turbines\(^6\) to operate on low to medium CV gases from 2 to 14MJ/m\(^3\), with quoted cycle efficiencies in the range 44-46%. More specifically, the syngas from the Chinchilla air-blown UCG project in Australia\(^7\) has been evaluated as an acceptable fuel for a 45MWe heavy-duty industrial gas turbine, in advance of the demonstration UCG power project planned for Chinchilla. Further performance evaluations on UCG gas have been undertaken at 400MWe for both the Chinchilla project and the proposed UCG power generation projects in China.

The UCG product gas, after gas clean-up, compression and adjustment, if necessary, of the gas composition (e.g. nitrogen dilution), would be used in a standard combined cycle as shown in Figure 2.9.

The field trial indicated that the UCG process can be interrupted and restarted over periods of at least one or two days without loss of the underground process. This important feature would allow the UCG operator to gain the value of peak-lopping prices, and to provide rapid ‘swing’ gas generation capacity, to balance, for example, the rapid variations in wind generation.

Other possible methods of power generation from UCG gas are to co-fire in a traditional thermal boiler operating on coal or other fuels, or to use a reciprocating gas engine, when only small power loads are involved. Generating efficiencies will be lower, but if existing or redundant plant were to be used, capital costs would be reduced. UCG gas might also be used for re-burn (as in Longannet Power Station, Scotland) to reduce NOX emissions from an existing coal plant.

**Firth of Forth UCG Study**

A study, entitled ‘The Coalmine of the 21st Century’ has been initiated by Heriot-Watt University, with support from the DTI, Scottish Enterprise and Scottish and Southern Energy Ltd. Its aim is to undertake a feasibility study of UCG in the substantial coal resources of the Firth of Forth. This study builds on work already undertaken as part of the initial search for a test site, and will establish whether this area offers prospects for large-scale UCG and power generation. If the one-year study is successful, a prospectus will be produced to attract investment funds for the development of the project.

**Current Worldwide Activities in UCG**

The recent International Workshop on UCG, undertaken as part of the UK initiative on UCG and held at the DTI Conference Centre in October 2003, has provided an up-to-date insight into worldwide activities on UCG, currently at a high level. The following is a brief summary.

Interest in underground coal gasification has increased substantially since the mid-1990s and most of it is now looking beyond experimental trials and towards commercialising the process for power generation and liquid fuel production. The motivation has varied from country to country but has been driven by the search...
for safer alternatives to small-scale coal mining (China), the desire to exploit unmineable coal (Australia) and as a replacement for diminishing local supplies of natural gas. Coal gasification with CCS, surface or underground, also offers a practical medium-term option for the continuing use of coal and a bridging strategy to eventual energy production with zero emissions, i.e. renewable energy and the hydrogen economy.

**Europe**

The European trial (1992-1998) and the subsequent UK initiative on UCG (1999 to present), described above, have been the most comprehensive investigation of UCG in deeper coal seams in the world to date. The trial has demonstrated the use of oil and gas technology to achieve high-pressure UCG in deep seams, and has also examined control and site selection for minimum environmental impact: essential stages in the development of an acceptable UCG operation.

A feasibility study by the Velenje Mining Company in Slovenia has been underway, which has identified UCG as a possible future route for the exploitation of a large lignite deposit currently being mined. Areas for a UCG trial, based on geology and hydrogeology considerations, have been identified and more detailed investigation and funding options are currently being considered. The thermal power station of 750MWe, adjacent to the mine, is a potential commercial user of the UCG gas, if the project were to be developed.

**China and Australia**

Chinese mining companies, with support from the Centre for Underground Mining Technology (CUMT), Beijing, have been working independently to develop their own form of UCG based on abandoned mine shafts. The programme has its roots in the Soviet programme, and a key feature is the use of a two-cycle process (alternate air and steam injection) to produce a high hydrogen product. China has five full-scale UCG trials currently underway, and about six have been completed over the past 10 years. The gas is distributed for local use, mainly for cooking and industrial heating. Plans are underway to build a 400MWe UCG power generation scheme within the next two years. The UK has recently completed a technology transfer programme on UCG with CUMT and the China International Centre for Economic and Technical Exchanges (CICETE), Beijing. The laboratory scale rig, see Figure 2.10, at CUMT could form the basis of a future collaborative programme on UCG.

The Chinchilla development in Queensland, Australia, is probably the closest UCG project to commercialisation. An independent company using expertise from the former Soviet Union has been operating a trial scheme for 30 months using simple air-blown vertical wells. The company is in the process of acquiring financial backing to install a 40MWe gas turbine and using the site as a semi-commercial demonstration. It was understood from the International Workshop that there is possible UK interest to exploit the Chinchilla technology in the UK.

The Australian State laboratory, CSIRO, has a well-established programme on UCG involving modelling and process.

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*Clean energy from UCG in China, Report no Coal 250, DTI/Pub URN 03/0611, February 2004*
assessment. It is proposing a trial at a site close to Chinchilla. A possible area of growing interest for Australia is the conversion of coal to liquid fuels.

**Other Countries**

Other coal-producing countries such as India, Pakistan, South Africa, Poland and Ukraine are considering the feasibility of importing or developing UCG technology to exploit coal resources. Japan (JCOAL & NEDO) continues to examine UCG for exploiting near-shore coal resources and is reconsidering the possibility of undertaking a UCG trial. To this end, the Japanese are providing some support to improve the instrumentation and data collection in one of the Chinese field trials.

Russia still has a small effort on UCG at the Skochinsky Mining Centre, Moscow, and private organisations in the USA are undertaking various feasibility studies and initiatives. The USA may also be reviving interest in UCG in view of the growing shortage of accessible natural gas in North America.

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**Conclusions on the relevance of overseas UCG activities to the UK**

*Much of the overseas activity to date has been concerned with shallow UCG, and is of limited interest unless sites can be identified that meet the environmental concerns raised in Chapter 3. There is some UK interest in the Chinchilla approach, assuming it can be adapted to UK conditions, and it is recognised by the developed coal-producing countries, (USA and Australia) that the protection of groundwater will be paramount.*

*If the UK decides that the economic and environmental advantages of UCG should be further pursued as a long-term option, the UK, through its Firth of Forth initiative, could be in a position to lead a UCG project. A possible alternative is to join the proposed Australian deeper UCG trial if it takes place. This is discussed further in Chapter 5.*
3. Environmental Emissions and Regulatory Position of UCG

Introduction

UCG is a potentially large-scale exploitation technology of fossil fuels such as natural gas, oil or coal, in which the delivered product is gas of low- to-medium calorific value.

In the past, a new fossil-fuel extraction process would have been considered in terms of its delivered price, convenience of use, reliability of supply, and the environmental issues of extraction, e.g. subsidence, habitat and groundwater contamination. Now, the carbon constrained world of climate change and the recent Energy White Paper require that the emission of greenhouse gases to air (CO₂, methane and possibly other minor gases) has to be considered. Furthermore, emissions are likely to bear a future cost under the European Emissions Trading Scheme.

Thus any new technology for fossil fuel energy conversion must be compared and assessed in terms of the ability, ease and cost of CCS as well as the other factors discussed above. A rigorous process of like-for-like comparisons is beyond the current study of UCG, but some evidence is already available.

Comparison with Other CO₂ Capture and Sequestration Technologies

The likely competing fossil fuel technologies for UCG are:

- IGCC.
- Supercritical thermal plant.
- Ultra-supercritical thermal plant.
- Oxygen-fired combustion.
- Natural gas-fired GTCC.

It is assumed that all UK fossil fuel technologies will require CCS, and that CO₂ sequestration in offshore reservoirs will have been developed over the 20-year timeframe required to commercialise UCG. Currently, however, there are considerable uncertainties about the cost-effectiveness and regulatory regime for sequestration. Even CO₂ capture processes, which are relatively well developed in the chemical industry, are not well costed on the scale of CO₂ capture from large-scale power generation.

Life-cycle Analysis

An Australian study⁹ compared life-cycle emissions (taking into account emissions of construction, operation and disposal of plant) based on the Chinchilla UCG project in Queensland (see worldwide developments in Chapter 2), against the competing technologies as shown in Figure 3.1.

This analysis indicates that on a life-cycle analysis, UCG-CCGT is ahead of all competing fossil fuel technologies with the exception of ultra-supercritical PF and natural gas.

Figure 3.1 is similar to the comparison of CO₂ emissions used in the DTI leaflet on UCG (October 2003) as shown in Figure 3.2.

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⁹ Australian Coal Association Research Programme (ACARP) study of Coal in a Sustainable Society, Case study B20, Electricity production using UCG, 2001.
CO₂ Capture from UCG Gas

Well-developed processes are available for the capture of CO₂ and the options include physical adsorption, chemical absorption and separation membranes. The pre-combustion processes for the capture of CO₂ are normally preferred for gasification processes such as IGCC on the grounds of efficiency and process costs, and the same would generally apply to UCG.

CO₂ capture in pre-combustion syngas is far more energy efficient than the post-combustion process (one fifth according to one estimate). A similar result should apply.

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10 The options were considered in the four sessions on carbon capture at the GHGT6 conference on Greenhouse Gas Control Technologies, Kyoto, October 2002
11 Putting Carbon Back into the Ground, IEA Greenhouse R&D Programme report, February 2001
12 Report on the 5th Gasification Conference, Amsterdam, April 2002, DTI visit report, K Fergusson
to CO₂ capture from UCG product gas, in spite of the additional steam reforming required to convert the methane. Operating pressure is also higher with UCG, which should reduce the energy requirements and plant costs.

Three options for CO₂ capture from UCG product gas are considered:

1. **Capture of CO₂ from the product gas, prior to combustion**
   For a high-concentration and high-pressure product gas stream such as UCG, the Selexol process, based on physical adsorption into an organic solvent and pressure swing for generation would be used to capture CO₂ in the products stream. The resultant CO₂ would be compressed to pipeline transmission conditions of 80bar for transmission to the sequestration site (see following section): the CO₂ product gas entering the turbine will also need to be compressed.

2. **Steam reforming and shift reaction followed by CO₂ capture**
   The mixture of methane and carbon monoxide in the UCG product gas can be converted to hydrogen and CO₂ by the standard process of steam methane reforming (SMR), which involves passing the gases over a nickel catalyst followed by shift conversion to achieve the following reactions:

   \[
   \begin{align*}
   \text{CH}_4 + H_2O &= CO + 3H_2 \\
   \text{CO} + H_2O &= \text{CO}_2 + H_2
   \end{align*}
   \]

   The resultant hydrogen and CO₂ mixture is passed to a Selexol unit for CO₂ capture and the hydrogen (with nitrogen added from the ASU) is used for power generation. SMR is a well-developed process for hydrogen production in the chemical and oil refining industries. Quoted plant costs are in the range 1800-5000/Nm³ of methane/hour, depending on plant throughput.

   The recently published design of an IGCC plant with a CO₂ capture option indicates that the shift process can be undertaken under acid conditions, and that the sulphur and CO₂ removal could be carried out in the same plant, allowing integration of the gas cleaning and CO₂ capture processes, and considerable capital cost savings.

3. **Post-combustion capture of the CO₂**
   An alternative is to remove the CO₂ from the exhaust gas of the power plant by post-combustion separation, although this is not usually advocated for gasification processes. Dilute CO₂ and nitrogen can be separated using amine solutions.

   A better process option, in theory, is to run the power plant at the end of the UCG gasifier on an oxygen/CO₂ mixture to produce only water and CO₂ in the resultant flue gas stream. This can then be dried and compressed for transportation to a sequestration site. Modifications are required to the combustion section of boilers and gas turbines, but work is already underway on advanced zero emission power concepts. Since UCG is already using oxygen for the underground process, oxygen-fired combustion could be a good match for the UCG power generation section.

Figure 3.3 shows the effect of the three methods of CO₂ capture on both the emission and production rate of CO₂. The total CO₂ production rate (emissions and capture) increases as a result of the energy required for the capture processes; at the same time emissions to atmosphere decrease as more CO₂ is captured. It is assumed that the efficiency of the capture process using Selexol is a realistic 90% of the CO₂ available. The no-capture case is shown as a base case for comparison – CO₂ ‘avoided’ is the difference between the CO₂ emitted in the capture and no-capture cases.

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13 Review of the case for a cleaner coal demonstration plant, report to DTI by Jacobs Engineering, available on DTI Cleaner Coal website
14 The Fluor Danial Econamine System is one such system
15 CO₂ control technologies: Alstom Power approach, T Griffin & A Bill, GHGT6 Conference, Kyoto, October 2002
16 Efficiency values extrapolated from DTI publication, Carbon Dioxide Capture and Storage – A Win-Win Option? May 2003, AEA Report ED 01806012
The results show that capture of CO₂ in the product gas alone reduces CO₂ emissions by about one third compared with the base ‘no-capture’ case. This option is considered further in the economics section, Chapter 4.

The pre-processing of the product gas before combustion increases the CO₂ avoided to 90%, which is the about the same as can be achieved with post-combustion capture. The difference is that the pre-combustion processing takes place at higher pressure with about one fifth of the volume, and the processing and capture plant can be smaller, and almost certainly less costly. The reformed and captured case is 95% hydrogen, and would be suitable, after further processing, for distribution in a future hydrogen economy.

**UCG and CO₂ Sequestration**

A UCG plant, like any other power generation plant with capture installed, is a source of relatively pure CO₂, which could be transported by pipeline and sequestered in a suitable storage location. Parallel projects within the DTI Cleaner Fossil Fuels Programme examine the options for CO₂ sequestration in the UK¹⁷ (which include enhanced oil recovery, and storage in deep saline aquifers or depleted gas reservoirs) and associated risks and environmental issues, so far as they can be evaluated at present¹⁸.

One of the possible UK scenarios for large point sources such as power stations is a pipeline network with access nodes connected to the offshore storage locations. A 300MWe UCG plant would be producing around 1.4 million tonnes CO₂/year and this would increase to around 10 million tonnes/year for the 2GWe offshore plants considered in Chapter 4. Even the lower figure would probably justify pipeline connections (~10km) to the nearest node.

Unmineable coal is a less attractive option for CO₂ disposal in the UK because coal permeability is generally considered to be too low, but directional drilling can improve access to coal seams and may offer limited scope for the future. There is also the possibility of using the abandoned UCG cavity and other stressed strata as a storage area for CO₂, but this is speculation at this stage.


¹⁸ The Intergovernmental Panel on Climate Change is producing a special report on CCS due in June 2005.
Groundwater Issues

The only commercial UCG plants ever built were in the former Soviet Union and the last of these was planned and constructed in the 1970s; no reliable environmental information is available on them. The first available environmental data on UCG came from the later USA trials, which were extensively monitored for groundwater contamination during and after gasification. UCG at shallow depth can pose a significant risk to groundwater in adjacent strata.

The European UCG trial at a depth of 550m was monitored for water contamination in surrounding boreholes, in the drinking water supply to the local community and in the local river for a period from initial site access to five years after the completed trial. No environmental contamination was detected at any of these monitoring points. The only evidence of contamination was in the water in the cavity itself, which is co-produced with the gas and brought to the surface. The main concerns of the Regional Authorities were surface spillage and disposal of contaminated water, for which special provision was made.

The Chinchilla project, Australia, took place under the supervision of the Queensland EPA but detailed results have not, so far, been made available. Questions were raised about the post-gasification process in the absence of a reliable large water supply.

A UCG project in the UK would require approval under the planning and environmental laws and should be consistent with Government energy policies on a low carbon economy and energy security, as set out in the Energy White Paper. The initial investigation revealed significant uncertainty in how UK and future legislation from Europe will affect UCG. Specialist consultants were contracted to initiate a study with the following objectives:

- Critically review the relevant environmental experience from previous UCG trials.
- Assess the UK environmental legislation applicable to UCG and identify issues that would need to be considered in presenting the process for approval by legislators.
- Propose best practice for the key stages of any UCG experimental and semi-commercial programme.

The study also examined the existing UK regulations that are likely to apply to UCG commercial operations, and any additional requirements that might be imposed by European environmental legislation, such as the Integrated Pollution Prevention and Control (IPPC) Regulations and the new Groundwater Directives. The extent to which the application of existing legislation would deal with wider concerns about controllability of underground coal fires, subsidence, escape of toxic gases and groundwater analysis was assessed. Work described later by the Tyndall Centre suggests that there would indeed be widespread concerns for onshore UCG.

Evaluation of Groundwater Risks

The Groundwater Regulations will require a prior investigation of any proposed UCG site and full consideration of the environmental risks. Most of the risk of wider groundwater pollution is governed by the natural characteristics of the site, namely the permeability of in-situ rocks and geological structures, hydrogeological conditions and the impact on local ground conditions.

A suitable UCG project site with the appropriate operational controls should present a very low risk to groundwater, but a robust assessment will be required. Close liaison with regulators and conservative approaches to risk assessment will need to be adopted, due to the uncertainties over contaminant generation, persistence, and transport through the geosphere. Furthermore, the understanding of the below ground environment from any practical programme of scout drilling from the surface will be limited.

19 Combustion News feature article on UCG, Ken Wa, September 2003
A network to monitor groundwater both during and after operations will be a requirement, the design of which will be site-specific and based on knowledge gained from the risk analysis. The mitigation response to pollution breakout, e.g. a rapid shutdown and clean-up procedure, will also need to be identified.

An important parameter in determining the risk in a UK context is to identify a zone of ‘permanently unsuitable’ (PU) groundwater. This is defined as a block of strata where the water quality and/or yield are so poor that groundwater in that area cannot realistically be regarded as an environmentally or economically significant ‘aquifer’. If a PU zone is established, the assessment of the pollution risk will focus on ensuring that there is no connectivity of the zone with overlying aquifers.

Although relaxations of the groundwater regulations using the concept of PU groundwater have been applied occasionally for hydrocarbon exploration, the principle needs to be tested, in the context of UCG. Suggestions for an environmental desk study based on a specific target area are proposed in Chapter 5.

**Operation of the Cavity and Shutdown Procedures**

Appendix 2 provides details about how the cavity should be operated and shut down to minimise the spread of pollutants. The basic strategy, tested in the Spanish trial, is to maintain a cone of depression in the groundwater around the reactor, so that the flow of contaminants is always towards the cavity. Monitoring of the pressure in the strata is required, and shutdown must avoid any build-up of steam or cavity pressure, which could lead to gas and liquid dispersal.

**Surface Issues**

Exploration, drilling, and the process of gas transport, gas treatment and power generation have well-defined surface impacts and risks which can be assessed using conventional methods, and these will be outlined in a Best Practice Guide for UCG. Appropriate mitigation will be required for dust, noise, visual impact and emissions to meet the necessary legislative standards (see below).

During operations, contaminated water is produced in the cavity from the gasification reactions, and reaches the surface with the product gas. The washing stage of the gas will also form contaminant solutions, which will have to be treated before discharge to local rivers or recycled as process water for the underground reactions. A UCG site will have a significant requirement for temporary storage of various process and contaminated water streams and will probably need its own small treatment plant nearby to recycle the water for further process operations. Control of spillages and the use of best practice in the processing of effluent waters will be an important part of site management.

**Surface Subsidence**

Significant surface subsidence is not thought to be likely because the boreholes and resultant UCG cavities from gasification will be narrow, compared with, for example, long wall mining, but this will have to be evaluated as part of the EIA. A multiple gasifier configuration for a large UCG scheme can be planned to minimise any adverse effects of subsidence.

The potential impact of ground movement on the permeability of strata and structures underground, caused by caving of the reactor, will have to be evaluated for its effect on the groundwater risk. The coal seam will be located well away from abandoned mines and shafts, but boreholes above the cavity for monitoring or production could be at risk and the effect of relaxation (for which there are various models) will need to be addressed.

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20 To be published: check DTI website on fossil fuel technologies


22 See UCG workshop presentations by Smart and Reddish et al, London, October 2003
Planning and Regulatory Issues
Planning Requirements

UCG is covered onshore in the UK by land use, planning and environmental regulation provisions. Land use planning provisions in England and Wales differ in some respects from those in Scotland and significantly from those in Northern Ireland. There is currently no spatial planning system offshore, thus each proposal would be considered on its merits. However, any gas recovered offshore would be taken to storage and power generation facilities onshore and these would fall within the ambit of planning provisions.

Development of a trial site for UCG, or of a full production facility, would be considered as a mining operation in any planning application. However, any associated electricity generation facilities would be regarded as an industrial facility. Therefore, policies concerning both mining and industrial operations would need to be taken into account by the relevant local planning authority. In the case of electricity generation facilities exceeding 50MWe in output, the responsible authority is the Secretary of State for Trade and Industry.

Under Town and Country Planning provisions, there is a presumption in favour of permitting planning applications, if environmentally acceptable, subject to suitable mitigation measures, where these are in conformity with policies in the minerals development plan. Since UCG is a recent issue in the UK there is an absence of specific policies concerning the extractive element of any proposal in development plans, and applications should be considered on their merits. However, there will be policies relevant to industrial facilities that are relevant to processing and generation facilities.

Where an application constitutes a Departure from the Development Plan, the planning authority informs the relevant Secretary of State who might either confirm that the planning authority should determine the application, or might recover the application for his or her own decision. If the local planning authority refuses an application, it may be the subject of an appeal to the Secretary of State.

In England, revised guidance on Planning and Minerals (Minerals Policy Statement 1 - MPS1) is in preparation to replace earlier guidance in Minerals Planning Guidance Note 1. This is likely to go to public consultation in 2004. While this will not refer to specific minerals, it will set out the general policy context. It is planned to consult on an Annex to MPS1 on ‘oil and gas’ later in 2004 and this will make some reference to UCG.

Account needs to be taken of the Environmental Impact Assessment (EIA) Regulations that apply to some forms of development. Since there is some uncertainty about the environmental impacts of UCG until a trial has been undertaken, it seems likely that a planning authority would require an EIA to be prepared in respect of any planning application. It would be wise to discuss this issue with the appropriate authorities at the earliest opportunity and determine, if appropriate, the scope of any Environmental Statement required.

Although extraction beneath the sea would not be within the ambit of land use planning, it again seems likely that EIA would be required for similar reasons.

Material information to the determination of a planning application may include, for example, impacts on the local environment, population and habitats. In the case of UCG, many of the issues associated with the storage and processing facilities would be similar to those of a broad range of industrial facilities. In the case of the extractive operations, drilling and dealing with associated impacts would be broadly similar to other forms of hydrocarbon exploration and extraction. Particular issues associated with UCG would include, however, the extent to which the operation can be controlled, the adequacy of the

Section Three
Environmental Emissions and Regulatory Position of UCG

23 The Planning and Compulsory Purchase Bill is likely to be the relevant legislation for England and Wales - the relevant legislation in both Scotland and Northern Ireland is different and further consultation is required
procedures for closure, and the potential impacts and containment of contaminants especially with regard to underground and surface water. Some of these matters are also the subject of environmental regulation (see below), and the planning conditions should complement, and not conflict with or duplicate, any licence conditions. Therefore, close liaison is required between the applicant, the planning authority and the environmental regulator.

Consideration will need to be given by the applicant to whether the extractive operation and any storage/generation should be co-located. The latter would be an industrial operation that might not be appropriate to a rural or greenbelt location but might be more acceptable on land already designated for industrial use in a development plan. The extractive operation would, however, even allowing for flexibility provided by directional drilling, need to be essentially within the area in which the mineral occurs. This might raise issues as to the acceptability of provisions for a pipeline between the sites. It might also lead to two separate local planning authorities needing to consider applications if the extraction and processing sites fell into different administrative areas.

**Integrated Pollution Prevention and Control and other EU Directives**

The UCG process, for both the trial and semi-commercial operation, would be covered by the Pollution Prevention and Control Regulations 2000. UCG, like all gasification processes, will need an IPPC permit from the relevant Environment Agency. IPPC requires the application and use of best available technology (BAT) for all emissions and detailed technical guidance is available, with revisions in preparation.

The EU IPPC Directive contains a research and development (R&D) exemption clause that was not fully implemented but is currently being undertaken across Europe. If the Regulations were to be modified to implement the R&D exemption, then any trial (but not a commercial UCG project) might be exempt from the full requirements of IPPC.

The gas processing has to ensure that the final emissions from the plant meet current air quality and emission standards for \( \text{SO}_2 \), \( \text{NO}_x \), heavy metals and particulates. The revised EU Large Combustion Plant Directive (LCPD) (2001/80/EC) aims to reduce acidification, ground level ozone and particulates by controlling emissions of sulphur dioxide, oxides of nitrogen and dust from large combustion plants. The Directive sets emission limit values for large (>50 MWt) combustion plant and is implemented in the UK through the IPPC regulatory regime. The LCPD states that compliance should be regarded as necessary, but not sufficient, to ensure compliance with BAT under the IPPC regime. Sectoral guidance for gasification plant under IPPC is not yet available, but eventually could add further conditions.

**Groundwater Regulations and the Water Framework Directive**

Approval under the Groundwater Regulations 1998 is part of the IPPC permit process. Normally, the release of contaminants to groundwater is prohibited, but the Regulations allow exemptions for pollutants such as phenols and heavy metals (List I & List II substances) for permanently unsuitable groundwater provided the substances cannot reach other aquatic systems.

The regulatory position at present is that UCG is likely to obtain groundwater consent if it can be established that:

- Adjacent groundwater can be declared permanently unsuitable (see earlier for a definition of PU groundwater).
- Transfer of contaminants to upper aquifers will not take place.
- Shallower aquifers are protected (leakage from access boreholes).
However, UCG is viewed as a novel process and risks may emerge as knowledge/thinking develops. Any site-specific applications of UCG will be determined on their merits.

Under the EU Water Framework Directive of October 2000, currently being transferred into UK law, the Commission in September 2003 put forward proposals for a ‘daughter directive’ for consideration initially by the Environmental Committee of the European Parliament, and later by EU Council Working Groups. In the daughter directive, abstractions of drinking water and discharges to groundwater will be more tightly regulated but Member States can still authorise exemptions for hydrocarbon extraction and mineral extraction. A clause26 similar to the definition of PU groundwater is included in the draft, which suggests that this exclusion will continue.

Other Relevant Legislation

Separate Air Quality Regulations were produced in England, Wales and Scotland in 2000, in which Local Authorities must review and assess the air quality in their region against set objectives. The emissions to air from the UCG operations could require controls to ensure that they do not cause any significant contribution to the ambient air concentrations and the means of regulating/enforcing these regulations would be via the Planning and IPPC permitting regimes.

In addition to the above planning and pollution regulations, UCG would have to comply with the ‘Control of Major Accident Hazards Regulations 1999’ (COMAH), the Air Quality Regulations and possibly other EU Directives now enshrined in UK law.

Licensing

It is anticipated that the drilling and exploration boreholes and the subsequent injection and production wells would require from the Coal Authority:

- An exploration licence.
- An operational licence to work the coal.
- A leasehold interest in the coal.
- An access agreement, where necessary, to pass through other coal seams.

In addition, a surface access agreement would be required from the landowner.

It is currently uncertain as to whether a petroleum exploration and development licence (PEDL) would be required, in addition to any licence that the Coal Authority would issue for UCG. An existing PEDL holder may also have to be consulted. These anomalies of the UK licensing systems need to be addressed, and is an action in this report.

Greenhouse Gas Emissions Trading

Commercial UCG operations rated at above 20MWh would come under the remit of the EU Emissions Trading Directive. Any installations established before the end of 2007 (the end of the first phase) would be eligible for allocation of free allowances under the New Entry Reserve, although the rules for allocation are still being discussed within Europe and allocations are not expected before the end of 2004.

Commercial UCG would fall under the second phase of the scheme, i.e. installations after 2007, in which there is considerable uncertainty as to whether CO2 allowances would be given, although discussions are taking place. UCG linked to CCS would require monitoring provisions to be agreed by the European Commission until a formal protocol can be established.

Safety Issues

Safety of the plant and below ground installation will be paramount in any future UCG operation, not only to protect people and property, but also to give confidence to the general public that a combustion process underground is fully controllable and safe from explosion and other hazards.

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26 Clause 31 “In cases where a body of water is so affected by human activity or its natural condition is such that it may be unfeasible or unreasonably expensive to achieve good status, less stringent environmental objectives may be set on the basis of appropriate, evident and transparent criteria”
All safety matters related to the drilling and operation of underground boreholes and extraction of hydrocarbon gas from onshore sites are covered by the Offshore Safety Division (OSD) of the Health and Safety Executive and a memorandum of understanding has been drawn up between the Mines Inspectorate and the OSD. Notifications are required under:

- The Offshore Installations and Wells (Design and Construction) Regulations 1996.

These regulations specify the procedures required for the design, planning, operation, supervision and abandonment of the process, and require that an independent well examiner oversees the written well examination scheme and the safety documentation.

A two-stage approval process is foreseen in which the project is divided into a construction, and an operational and abandonment phase. Approval of the UCG operations from a safety standpoint will require detailed consideration of the underground ignition, gasification and associated activities; significant effort will be required to develop and agree the necessary documentation with the OSD.

The above-ground plant for oxygen supply, gas clean-up and power generation may be located some distance from the wellhead configuration and connected by transmission pipelines. These will be subject to the normal safety regulations for industrial plant; namely, the Health and Safety at Work Act 1974 and COMAH 1999.

### Public Awareness Issues

The general public are largely unaware of UCG, although there have been occasional articles in national newspapers and the popular scientific press. The first site to be considered for a UCG trial was an abandoned colliery at Silverdale, Staffordshire, where planning permission was sought in 2000 to construct the wells for a UCG trial by directional drilling. This provoked significant local reaction, in spite of the public consultation undertaken by the Coal Authority. The issues of concern are summarised in Table 3.1.

#### Table 3.1 Issues of concern raised by local people at Silverdale Colliery (year 2000)

<table>
<thead>
<tr>
<th>Drilling issues</th>
<th>UCG gasification issues</th>
<th>General issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Noise</td>
<td>Fear of uncontrollable coal burn underground</td>
<td>Fear of coal catching fire and burning uncontrollably, the area has a history of ‘spontaneous combustion’ and this issue was high in the awareness of local people</td>
</tr>
<tr>
<td>2 Visual impact of the drilling rigs</td>
<td>Waste from the UCG contaminating aquifers. In particular, coal tars which are believed to cause cancer</td>
<td>The area is considered to be cleaner and ‘better’ since the colliery closed, particularly dust and air pollution</td>
</tr>
<tr>
<td>3 Increased traffic: one resident estimated the number of vehicle movements at 700 HGV movements over the course of the project</td>
<td>Danger from underground explosions</td>
<td>The experimental nature of the work was questioned, with people not wishing for a scheme to go ahead when some of their questions could not be answered. A residential area was not seen as suitable for research with many unknowns</td>
</tr>
<tr>
<td>4</td>
<td>Gaseous emissions from UCG could rise to the surface</td>
<td>Regeneration of the local area would be delayed and firms would be ‘put off’ from locating near the site</td>
</tr>
<tr>
<td>5</td>
<td>Subsidence: the area has a history of subsidence</td>
<td>The scheme did not bring any benefit to Silverdale</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>The value of local property would be reduced</td>
</tr>
</tbody>
</table>

27 Extracted from ‘The Public Perceptions of UCG: A Pilot Study’, Report to the DTI by the Tyndall Centre, UMIST, December 2003
A lesson from Silverdale is that the local social, cultural and institutional context will have great influence on the manner in which the risks and benefits associated with UCG are perceived. Familiarity of local people with the consequences and legacies of conventional coal mining amplified the perceptions of risk of affected people and, overall, local context will be an important factor in site selection.

The Tyndall Centre at UMIST28 undertook a pilot study of the public perception issues of UCG based on desk and a focus group discussion. It found that UCG is likely to be perceived by the public as a potential high-risk project with little to offer local communities.

On the other hand, the potential of UCG as a secure source of energy for the UK, and its potential for lower cost CO2 capture was seen by the focus group as a good safety net for the UK. Suggestions were made for improving public perception of UCG and integrating it more closely within a sustainable energy programme. The focus group felt that there are net economic benefits to be reaped if the UK comes to acquire a technical mastery of the process and can export the technology overseas.

Some of the ways suggested by this study in which these challenges might be addressed are to:

- Develop UCG on a small scale in order to obtain technical mastery of the process and potential innovations in an incremental fashion.
- Include the benefits of CCS from the start of any project and pay particular attention during planning to ensure that the life expectancy of UCG correlates with the bridging policy of CCS prior to full commercialisation of zero emission energy.
- Include UCG within a package of measures aimed at improving the local community’s quality of life, economy, environment and employment.
- Ensure all operators and other responsible parties are transparent and open in their dealings with the public and regulators, providing clear and accurate information and also providing local residents with the opportunity to cross-examine the information, developers, technical experts and regulators.
- Include the local public and stakeholder reactions as part of the site selection process, alongside the more tangible issues such as coal geology, hydrogeology and other planning issues.
- Undertake a professional communication strategy, before (and after) any trial site is selected, including setting up of an information web site and the production of other suitable publications.

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28 University of Manchester Institute of Science and Technology
Conclusions on the environmental issues of UCG

As a coal-based technology, UCG will need to pay particular attention to CO₂ emissions. Any large-scale development is only likely in the context of carbon capture and storage, which entails solving a particular range of issues. The processes required for CO₂ capture from UCG product gas are available and the higher pressure of the gas may be an advantage. Work is underway on CO₂ sequestration within the UK and internationally via the IPCC and the Carbon Sequestration Leadership Forum.

Groundwater contamination is another primary concern with UCG, and will need to be fully evaluated for any proposed UCG project. Factors which can reduce the risk of contamination are site selection, deeper coal seams and operating the cavity as a local depression within the strata.

Groundwater Regulations are met when the target coal seam is located in an area of ‘permanently unsuitable’ groundwater, but this has to be proven by environmental investigation and analysis, and the concept still has to be tested in the context of UCG at specific sites. An investigation of a specific site and a probabilistic risk analysis are proposed.

The framework for approval of a UCG project is a permit under the IPPC Regulations. The utilisation of UCG product gas at the surface will have to conform to European Directives for large power plant, the UK air quality requirements and any future further restrictions that might be imposed on gasification plant. Although air emission controls are stringent, the technology of mitigation is fully developed and UCG will have no special difficulties in meeting current and future regulations.

The Town and Country Planning Acts of England and Wales and the equivalent in other parts of the UK give opportunity for local communities to object to any proposed UCG project, and this could impose significant restraints on the exploitation of UCG in rural areas. On the other hand, planning regulations recognise that minerals have to be extracted where available, including rural areas, and there is a presumption in favour of permitting planning applications if environmentally acceptable.

Regional variations can be anticipated and planning applications for real sites, with appeals if necessary, will resolve whether UCG is an acceptable method of coal exploitation.

Licensing of UCG operations under the current arrangements through the Coal Authority should present no difficulties, although the position with respect to the licensing of oil and gas operations still needs to be established.

The pilot work on public perceptions suggests possible cautious ways forward, and for UCG in rural coal areas, the power plant will need to be located away from the UCG extraction station in an appropriate industrial area. UCG under estuaries and under water near to shore are seen as the best prospects for early project entry in the UK.
4. Economics and Commercialisation of UCG

Economic Scoping Evaluation of UCG

A preliminary economic evaluation has been made of UCG for a UK onshore situation. Four case studies for UCG have been considered:

| Case 1: | 50 MWe small-scale integrated UCG power plants. |
| Case 2: | 300 MWe large-scale UCG linked to a remote power plant. |
| Case 3: | 300 MWe as above with post-combustion CO₂ capture. |
| Case 4: | 300 MWe as above with partial pre-combustion CO₂ capture in the product gas. |

The assumptions and full details used in the economic assessment are available in a separate report. Three options can be considered for capture from UCG product gas, namely:

- Total CO₂ capture in the flue gases.
- Partial pre-combustion capture of the CO₂ in the product gas.
- Total pre-combustion capture after converting the product gas to H₂ and CO₂ using a steam reforming and shift stage.

The first two have been costed, but plant data were unavailable for the total capture of CO₂ from the pre-combustion gas, even though this is the most likely approach to UCG-CCS. Within the approximations of this scoping study, it is assumed that the costs of total CO₂ capture will be the same for post and pre-combustion processes.

Gas Production Panels

It is assumed in the economic assessment that a single UCG channel of the type shown in the early sections of this report will produce around 25MWt on a continuous basis, and these would be grouped into branched modules to feed the production well, as shown in Figure 4.1.

In all of the case studies, a UCG panel consists of a coal panel 500m x 500m with four adjacent areas, 250m by 250m, in a coal seam of 2.5m thickness, each accessed by a single injection well. The gas output from the four areas is collected by a single production well located in the centre of the panel. The total thermal output of each panel, using assumptions based on field trial data, is estimated to be 10,400GWh, which is equivalent to 3.2MWh/tonne of UCG coal resource.

A number of panels working simultaneously would be connected by pipeline to the power and processing island, possibly some distance away. Each panel would typically have a production life of 1-3 years, depending on the rate of gas production, and once exhausted, and safely shut down, the well would be sealed and the surface returned to its original rural or other state. The pipelines would then be connected to the fresh coal panels, which would have been pre-drilled and prepared in advance.

Figure 4.1 Configuration assumed for a UCG production panel (500m x 500m)
The panels do not need to be adjacent, and multi-seam applications can also be foreseen, which could allow the production wells to be re-used.

The total development cost of a panel is estimated at £9.3 million and is equivalent to capital intensities of £15.2 per tonne of coal accessed and £2.8 per MWh (£0.79 per GJ) of UCG gas produced. It was assumed that the maximum rate of production from a panel would be about 100MW (thermal) and that the UCG product gas, after drying and cleaning, would have a calorific value of about 13MJ/Nm³ (cf natural gas 38.5MJ/Nm³).

It is anticipated for Case Studies 2-4 that oxygen would be supplied by pipeline from the distant power island, and only equipment required for the wellhead operations would be installed at the field production station. The temporary field site at the surface would consist of wellheads, the mechanical equipment for coiled tubing injection, a production platform and a facility to store water for the process, initial gas cleaning and emergency quenching. The time period for land use from initial drilling of the panel to land restoration would be about 5-8 years. No appreciable surface movement is expected with the proposed cavity pattern.

Analysis and Results

All of the economic analysis was carried out in pounds sterling. A capital charge (discount rate) of 10% real was used throughout the assessment to represent the rate of return likely to be required from commercial organisations. All of the case studies were assumed to have a 20-year operating life, with an average load factor of 80%.

Three sets of results have been developed:

- Cost of electricity.
- Cost of electricity with carbon dioxide capture.
- Cost of carbon dioxide capture.

In each case, these results are compared to data for conventional coal and natural gas power plant that were produced as an input to DTI’s Review of the Feasibility of Carbon Dioxide Capture and Storage in the UK.

Cost of Electricity

The cost of electricity generation from UCG without carbon dioxide capture was estimated for Case Studies 1 and 2. These results are compared to the generation costs from standard IGCC and GTCC plant in Figure 4.2. Within the uncertainty of the analysis it appears that large-scale UCG-based power generation (Case 2) has a cost comparable to natural gas-fired GTCC and somewhat less than modern conventional coal-fired IGCC technology.

IGCC (1) is based on data for a capture ready IGCC design from Jacobs Consulting while IGCC (2) is based on data from an IEA GHG Programme report. In contrast, the Case 1 scheme has substantially higher costs. Furthermore, UCG can respond to diurnal swings in power demand, thereby increasing its value as a peak supplier.

![Figure 4.2 Comparison of the generation costs of UCG schemes with conventional fossil fuel technologies](image-url)
Cost of Electricity with Carbon Dioxide Capture

The cost of electricity generation from UCG with CO₂ capture was estimated for Case Studies 3 and 4. These results are compared to the generation costs for standard IGCC and GTCC plant with CO₂ capture in Figure 4.3. UCG-based power generation with partial CO₂ capture at the gasification site is only marginally more expensive than generation without capture – Case 2 and its power generation costs are highly competitive to other capture options. However, this technology produces considerably more emissions than the other capture options included in Figure 4.3 below.

Case 3, which involves 85% capture of the CO₂ in the power plant flue gas, has a generation cost that is competitive with IGCC (2). Both are significantly more expensive than the IGCC (1) design or with capture applied to a natural gas-fired GTCC.

In the UK the lowest cost plant at present is GTCC fired with natural gas, and therefore it is reasonable to assume that this technology would be the preferred choice for any new capacity required by the system. If a CO₂ capture plant were built in preference to a GTCC plant, then the cost of CO₂ capture would be the difference between the generation cost of a new GTCC and that of the plant fitted with capture technology.

Using this relationship, capture costs for Cases 3 and 4 have been estimated and are compared with a conventional fossil fuel IGCC and GTCC plant in Figure 4.4.

The capture of CO₂ from the flue gas of the UCG-fuelled combined cycle, Case 3, has costs comparable to conventional power plant. Case 4 has a much lower cost but only limited capture of CO₂ from the medium calorific value gas (see dry gas composition in Figure 2.7), and this is likely to be unacceptable in a carbon-constrained world (say 20 years ahead). If comparable levels of CO₂ capture are required (85-90%), then the methane in the product gas will have to be reformed (to CO and H₂) before the shift and capture stages, but this has not been costed to date because plant costs are not readily available.

The results are summarised in Figure 4.5, as a plot of electricity costs versus emissions for all the cases considered in the economic analysis.

The results show that the three competing technologies of GTCC, IGCC and UCG, within the uncertainties of the analysis, follow a trend of increasing cost as emissions are reduced. GTCC provides the lowest costs for both the capture and the no-capture cases. The two coal technologies of IGCC and UCG are difficult to differentiate since UCG with capture lies between the two IGCC cases with capture and, on the evidence to date, the two are comparable. A more detailed process cost study of UCG compared with IGCC and supercritical PF is clearly required.

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Figure 4.3  Comparison of the generation costs of UCG schemes with conventional fossil fuel technologies, all with CO₂ capture

Figure 4.4  Comparison of the CO₂ capture costs of UCG schemes with conventional fossil fuel technologies

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34 Generation costs for IGCC and GTCC plant assumed fuel costs of £30.5/tonne and 23p/therm respectively
Conclusions from the economic scoping analysis

An initial economic assessment has been made for a range of options for implementing onshore UCG combined with power generation. This has used existing technology data which have been interpolated, as necessary, and adapted to fit the cases being considered. Consequently, the estimates are likely to involve an uncertainty exceeding +/-30%, and therefore only broad conclusions can be drawn from the results. The main findings are:

1. Large-scale UCG with power generation (300MWe) undertaken remote from the gasification site has a generation cost comparable to, and possibly less than, conventional coal-fired IGCC technology. However, small-scale developments (~50MWe) are not likely to be economically viable as stand-alone projects.

2. UCG combined with power generation and CO\(_2\) post-combustion capture has a generation cost which lies between the two estimates for conventional IGCC with CO\(_2\) capture. In practice, the CO\(_2\) will be captured in the product gas prior to combustion, but data were not available to cost this option.

3. The cost of CO\(_2\) capture (again post-combustion) with UCG and power generation is comparable to the capture cost of CO\(_2\) from natural gas-fired GTCC.

4. It is possible to undertake a limited level of CO\(_2\) capture by separating CO\(_2\) present in the medium calorific value gas emerging from the underground gasifier. This has a lower capture cost than other options but captures only about 25% of the CO\(_2\) associated with power generation. This option is unlikely to be attractive in the future carbon-constrained world.

5. The option to separate a larger proportion of the CO\(_2\) through pre-combustion capture has not been covered by this assessment. This would involve reforming the methane in the product gas to CO and H\(_2\) and then shifting the CO to produce additional H\(_2\). This would yield similar abatement levels to the post-combustion separation of Case 3 but may have advantages regarding energy efficiency.
Potential UCG Sites in the UK

UCG Small Trial Sites

A systematic search by planning and mining consultants was undertaken to find potential UK trial sites for UCG. The initial specification called for a small trial site of 500m x 200m located above a suitable coal seam(s), where directional drilling and single channel UCG tests would be conducted. The target coal seam for the search was bituminous or sub-bituminous coal, greater than 2m thick, depths between 600 and 1200m, separation of at least 500m from abandoned mineral workings and a well-defined reserve of initially 60,000 tonnes.

A detailed examination, covering coal geology, hydrogeology, and environmental issues, identified potential areas where a trial might be conducted. One of the better prospects is the Firth of Forth, discussed in Chapter 2. Other possible sites considered include South Wales near Port Talbot and areas previously identified by British Coal as future mining prospects. The latter were mostly located in rural areas, where the consultants thought that planning permission for the trial would be more difficult, although not impossible.

The new Heriot-Watt study (Chapter 2) will re-examine the whole of the Firth of Forth, where massive areas of coal exist both at Longannet and further along the Fife coast. The outer zone of the estuary has potential CO₂ sequestration sites which will also be investigated.

Commercial Opportunities in the UK

The total volume of onshore coal in the UK, confirmed as having good UCG potential, is estimated from the resource study, Chapter 2, as 17 billion tonnes of coal or 300 years based on current UK consumption of 58 million tonnes/year. Table 4.1 shows the key resource areas for UCG in order of size.

The detailed maps from the resource study show that the majority (>80%) of this resource lies in rural areas, although important exceptions exist under rivers (Mersey, Forth and Trent) and some of the industrial areas of Lancashire, Yorkshire and the central area of Scotland. In a few cases, the power plant could be placed directly above the coal seam, but most applications in the UK will require the power and processing plant to be separated from the UCG, as considered in the economic analysis above.

UCG Large-scale Production Sites

The economic assessment of UCG outlined above suggests that production plants of 300MW e and above give significantly lower costs of production, which are competitive or lower than other coal processes. Another advantage of larger plant is that CO₂ capture and transmission become more economic.

Table 4.1 Summary of UCG resource in England, Scotland and Wales (UK Resources Study, 2003)

<table>
<thead>
<tr>
<th>Area</th>
<th>Average thickness of coal meeting UCG criteria (m)</th>
<th>Area of resource (km²)</th>
<th>Volume of coal for UCG (million m³)</th>
<th>Quantity of coal (million tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yorkshire/E. England</td>
<td>3.5</td>
<td>1397</td>
<td>4866</td>
<td>6326</td>
</tr>
<tr>
<td>Lancs/Dee</td>
<td>7.6</td>
<td>483</td>
<td>3669</td>
<td>4770</td>
</tr>
<tr>
<td>Midlands/Staffs</td>
<td>5.6</td>
<td>445</td>
<td>2506</td>
<td>3258</td>
</tr>
<tr>
<td>Warwick/Oxford</td>
<td>3.4</td>
<td>457</td>
<td>1569</td>
<td>2040</td>
</tr>
<tr>
<td>Wales</td>
<td>7.0</td>
<td>24</td>
<td>169</td>
<td>220</td>
</tr>
<tr>
<td>Scotland</td>
<td>3.1</td>
<td>43</td>
<td>132</td>
<td>171</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td>2849</td>
<td>12911</td>
<td>16785</td>
</tr>
</tbody>
</table>

CD-ROM available on request from Cleaner Fossil Fuels Programme Helpline helpline@cleanercoal.org.uk
A preliminary exercise has been undertaken on the key areas for onshore UCG in the UK, to establish the potential size of UCG in the UK. The basis of this investigation was the identification of practical locations for power production and gas processing plants, and the estimation of plant sizes based on the available UCG coal resource within distances of 5 and 25km of the plant, and conservative assumptions about the availability of the coal resource for UCG (see Appendix 3 for more details of the calculation).

Three of the five areas identified have power stations located in the area and two have IGCC planned (South Yorkshire and Port Talbot). The UCG production plants could replace or augment the existing facilities. The potential for onshore production of UCG based on this preliminary study is summarised in Table 4.2.

The potential for UCG in these areas depends on how far it is economical and locally acceptable to extend the reach of the power station. The results indicate that the available power generation capacity is increased by a factor of nearly eight if the catchment area is extended from 5 to 25km from the power station location. The largest areas for onshore UCG are around the River Dee, Lancashire and Yorkshire. Central Scotland is smaller but has the advantage that most of the UCG coal is within 5km of the Longannet area. It is worth noting that Teesside is currently considered one of the best areas of CBM exploration, and that UCG and CBM could compete for the same coal in this area. In a multi-seam application, there may be synergies between the two techniques, used on different seams.

The total of 27.2GWe is larger than the current UK installed coal-fired generating capacity of 25GWe, and UCG has the potential to replace about 60 million tonnes/year of combined mining and coal imports which is approximately the current annual UK consumption of coal (58 million tonnes in 2002). Other options for UCG production gas could be considered and include:

- Co-firing existing IGCC or GTCC power stations with UCG gas (possibly as re-burn to reduce emissions).
- Smaller scale distributed power plant of 40-100MWe with combined heat and power.
- A supplier of variable load, including peak lopping.
- Conversion of the syngas to hydrogen production (with CO₂ capture) for local distribution, transport or power production in large-scale fuel cells.
- Conversion to synthetic natural gas to augment reducing supplies of indigenous natural gas.

### Offshore UCG

A UCG operation in shallow offshore waters is an attractive option because very thick coal seams are known to exist in large deposits in the North Sea. Furthermore, potentially redundant drilling and production platforms are already in place in the areas of interest and possible CO₂ sequestration sites.

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**Table 4.2 Summary of the potential for onshore UCG power stations in the UK**

<table>
<thead>
<tr>
<th>UCG power station site</th>
<th>Power output based on coal within 5km (MWe)</th>
<th>Power output based on coal within 25km (MWe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longannet area, Fife</td>
<td>410</td>
<td>490</td>
</tr>
<tr>
<td>Selby/Drax Area, Yorkshire</td>
<td>810</td>
<td>4,800</td>
</tr>
<tr>
<td>South Yorkshire</td>
<td>900</td>
<td>7,100</td>
</tr>
<tr>
<td>Mersey/Dee area, Lancashire</td>
<td>1,400</td>
<td>14,100</td>
</tr>
<tr>
<td>Port Talbot, South Wales*</td>
<td>0</td>
<td>730</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>3,520</strong></td>
<td><strong>27,220</strong></td>
</tr>
</tbody>
</table>

(*potential for UCG resource in Port Talbot Bay not considered*)
(aquifers, enhanced oil recovery opportunities, and unmineable coal) could be in close proximity. The UCG product gas could be brought to shore for processing and power generation (possibly using existing pipelines) at suitable industrial locations.

Technically, the 50-100m of sea depth is unlikely to present additional difficulties which have not already been solved by the oil and gas industry. Environmental constraints, although still important, will be less restrictive for the siting of the wellheads and surface platforms.

The main problem of offshore UCG is likely to be safety and cost. The safety issue arises largely from the need to generate and supply oxygen to the injection well and the higher temperatures and ignitability of the product gas compared with, say, natural gas. The cost of locating and supporting equipment on offshore platforms is much higher than land-based operation (an approximate estimate is three times the cost) and, as far as possible, gas processing, plant control and power production should be kept to a minimum offshore.

The extra cost might also be offset against an increase in the scale of operations, which should be comparable with current gas production platforms, typically 1-20 million m³/day, which is equivalent to between 120 and 2,500MWt of energy available for power generation. Another factor in its favour is the thicker coal seams, which would extend the production life of the coal seam and require a lower accuracy of drilling.

Figure 4.6 suggests how UCG platforms located on the offshore coal deposits would be connected by transmission pipeline to an existing gas reception terminal, in this case Easington near Hull, where the production gas would be processed before use in a GTCC plant. An alternative would be to transfer the gas to an existing nearby power station, such as Drax, Yorkshire.

While offshore UCG is an area of promise and future study, the commercial process will need to be developed first on land or very close to shore (e.g. estuaries) before the higher costs and risks of offshore operation are attempted.
Development of UCG

The route to commercial development of UCG is through trial and semi-commercial demonstration with supporting paper studies. A development programme for commercial scale would take about 8-10 years to complete, on previous experience.

Potential for Overseas Collaboration

Interest in UCG is currently at a high level and the principal activities have been described in Chapter 2. Feasibility studies and trials are underway in many coal-producing countries, including India, Australia, South Africa, China, Japan and Slovenia, and there is some possible renewal of interest in the USA. The UK is clearly leading the activity on UCG in laterally drilled coal seams, although others are starting to show interest.

The current trials in China and the Chinchilla project in Queensland, Australia, are taking place at shallow depth using technology which may need adaptation for use in the impermeable UK coals. Some of the modelling and laboratory back-up work in China may be relevant to future developments in the UK.

The feasibility studies being initiated in Velenje Mine, Slovenia, and by IST, Portugal, may be more promising for the UK, but both are at an early stage. Both are seeking and are likely to rely on EU funding.

The three prospects for overseas collaboration which are relevant to the UK, in order of priority, are:

1. Capitalise on the growing US interest (DOE and private interests) in gasification as a method of producing hydrogen and to avoid the previous environmental problems of UCG. The recently signed MOU on fossil fuels between the US and UK Governments may provide a future route for collaboration.

2. Investigate the Australian demonstration of UCG, involving Government (CSIRO) and private interests. UCG has been identified and a new company to progress the development has been formed. The UK has been invited to participate.

3. Collaborate with the Chinese on UCG. The use of abandoned or man-made galleries is not suitable for the UK, but the Chinese programme is large and some of the basic research work may be relevant. The Chinese would be prepared to host a UCG trial but would expect the technology and probably most of the funding to come from outside. The Japanese are already providing technical input on data analysis to the Chinese trials.
5. Conclusions and Recommendations

Conclusions of DTI Initiative on UCG

1. Carbon Abatement Technologies (CAT) Strategy
   - On the assumption that all future fossil fuel technologies will be associated with CCS, the UCG option compares favourably with IGCC, GTCC and super/ultra critical PF.
   - UCG is a process that lends itself to CO₂ capture both from the high-pressure product gas and from subsequent downstream processing, using existing process technology.
   - Scoping estimates of the economics of UCG-CCS suggest that costs of electricity with post-combustion CO₂ capture are competitive with the other main coal alternatives, namely IGCC-CCS. Although not costed, pre-combustion processing of the UCG product gas might reduce still further the CO₂ capture costs for UCG-CCS.
   - A comparison of life-cycle CO₂ emissions places UCG lower than IGCC, supercritical PF and PFBC, and is only higher than GTCC, renewable sources and ultra-critical PF.
   - Potential CO₂ sequestration sites are located in close proximity to the favoured estuary and near-shore sites for UCG exploitation, e.g. Firth of Forth and off the Lincolnshire coast.

2. Security of Supply
   - As conventional mining declines and natural gas supplies in the UK Continental Shelf become exhausted, the UK is becoming a net importer of energy. Half of the coal is already imported and in 20 years’ time, the UK will be reliant on imported sources of energy unless there is a revival in mining or much more natural gas is discovered.
   - UCG offers a potentially practical route to exploitation of the indigenous coal resources provided the initial economic estimates prove correct and the environmental concerns can be overcome.
   - The UCG share of UK energy supply could be as large as the current coal-fired component, and would last until renewable energy is fully commercialised.
   - The UCG option for UK energy supply will provide security of supply in the face of increasing supply and cost uncertainties in the energy market.

3. Hydrogen Economy
   - UCG product gas, like IGCC, can be readily converted into hydrogen and CO₂, through the shift and capture processes. Large-scale gasification of coal is a practical alternative to natural gas reforming.
   - The hydrogen could be used directly in a stationary fuel cell at high efficiency, or distributed in a hydrogen infrastructure for transport.
   - The high turn-down capability of the UCG process adds considerably to its potential as a future option for hydrogen production. Further process investigation is justified in this area.

4. Groundwater Issues
   - Groundwater contamination is a primary concern with UCG, and will need to be fully evaluated for any proposed UCG project. Factors that can reduce the risk of contamination are site selection, deeper coal seams and operating the cavity as a local depression within the strata.
Operational failure of boreholes, wellheads, etc could lead to environmental contamination, and there is a small risk of subsidence from cavity caving. These risks can be largely minimised by effective exploration techniques (boreholes, logging, seismic surveying).

An investigation of a specific site involving environmental testing and modelling and a probabilistic analysis of all the risks are proposed.

5. UK Coal Resources

The resource study has shown that UK coal resources suitable for deep seam UCG on land are plentiful and amount to 17 billion tonnes or nearly 300 years’ supply at current consumption), and this excludes at least a similar tonnage where the coal is unverifiable for UCG. The detailed maps show that the largest areas are in Yorkshire, Lincolnshire, the Dee area and Warwickshire, with smaller deposits in Central Scotland and South Wales. Most of the coal seams with potential for UCG are located in rural areas, but important and useful exceptions exist under rivers and brownfield areas.

The most promising early targets for UCG in the UK are rivers and estuaries, which could be accessed from brownfield sites along the shoreline, where the drilling, process and power plants would be located. Opportunities are likely to exist in the Firth of Forth, the Dee Estuary and around the River Humber.

A preliminary exercise based on conservative assumptions for power plant location and coal seam access suggests that large UCG power projects could be located in at least five brownfield areas. If these sites had access to temporary satellite UCG stations within 25km of the generating plant, an estimated 27GWe of electricity could be generated over at least 20 years. This is greater than the current generating capacity from coal in the UK.

6. Planning and Public Perception

The experience of the attempted planning application at Silverdale Colliery, and the pilot study of public perceptions suggest that the public will be concerned about factors such as uncontrolled combustion, escape of pollutants, groundwater contamination and subsidence. Although technical solutions exist, the conclusion is that planning restrictions and public perception will impose significant restraints on the exploitation of UCG in rural areas.

The Town and Country Planning Acts of England and Wales and the equivalent in other parts of the UK give ample opportunity for local communities to object to any proposed UCG project. Planning regulations, on the other hand, recognise that minerals have to be extracted where available, including rural areas, and there is a presumption in favour of permitting planning applications if environmentally acceptable.

Regional variations can be anticipated and planning applications for real sites, with appeals if necessary, will resolve whether UCG on land is an acceptable method of coal exploitation in the longer term.

UCG under estuaries and in near-shore waters with the power and processing island located on a brownfield onshore site is seen as the best prospect for early project entry in the UK. The step to offshore UCG could then be within reach, see below. Potential sites in the Firth of Forth are being identified as a first stage in this process.
7. Regulatory Issues

- The framework for approval of a UCG project is a permit under the IPPC Regulations. The utilisation of UCG product gas at surface will have to conform to the LCPD, the UK air quality requirements and any future further restrictions that might be imposed on gasification plant through EU IPPC guidance notes (known as BREFs). Although air emission controls are already stringent, the technology of mitigation is well developed and UCG should have no special difficulties in meeting current and future regulations.

- Groundwater Regulations are likely to impose a challenge to the regulatory approval of UCG. Groundwater Regulations can be met when the target coal seam is located in an area of ‘permanently unsuitable’ groundwater without communication to existing aquifers. This must be proven by environmental investigation and analysis, and the concept still has to be tested in the context of UCG at specific sites.

- Licensing of UCG operations under the current arrangements through the Coal Authority should present no difficulties, although the position with respect to the licensing of oil and gas operations still needs to be established.

8. Offshore UCG

- The offshore coalfields in the lower North Sea hold considerable promise for large-scale UCG. Potentially, redundant drilling and production oil and gas platforms could be used for the offshore production of UCG gas, which would be brought ashore, possibly in existing pipelines, for processing and power production. Potential CO₂ sequestration sites, such as aquifers, EOR opportunities and unmineable coal, could be in close proximity.

9. UK Industry and Export Potential

- The UK has related expertise in the various technologies of UCG, particularly in the surface plant and hardware required for a UCG process, i.e. air separation, gas cleaning, CO₂ capture and power generation. The UK has key knowledge of the geological selection process, environmental issues and the underground processes themselves of UCG. Only in directional drilling in coal is the UK currently lagging behind its overseas competitors, but this is compensated by relevant directional drilling expertise associated with North Sea oil and gas.

- Offshore UCG, if successfully developed, would use much of the expertise in platform design and servicing that already exists in the UK to support the oil and gas industry. As North Sea production of conventional hydrocarbons decreases, these UK industries will require new markets for their advanced drilling and platform expertise and offshore UCG presents an opportunity with considerable technological synergy. The market potential for the technology would be very significant; for example, Japan has large offshore coal deposits. Feasibility studies of UCG are underway in Australia, Asia, South Africa and various parts of Europe. These studies, if successful, could lead to the supply of gas processing power and drilling equipment. In China, opportunities exist for the UK to export power generation and gas cleaning equipment. A co-ordinated policy on the export of UCG technology could lead to a demand for UK equipment and services.
Conclusions on the Technical Status of UCG

1. The UCG field trials confirm that this technology does have potential. The reliability of inseam gasification between vertical boreholes has been achieved by the techniques of directional drilling (UK, USA and Europe), man-made galleries (China) and closely spaced vertical boreholes (Chinchilla, Australia). Inseam drilling in deep seams is the favoured option, in the long run, to meet UK environmental regulations, and there are advantages in operating at high pressure.

2. For deep UCG, further field investigation (at least one trial, and a semi-commercial scheme) would be required to obtain operational and environmental data, before a full-scale ‘bankable’ project, with acceptable financial risk, could be considered for construction. The key unknowns are sustainable gasification over long inseam wells (>200m in length), the branch drilling of borehole networks for commercial-scale operations, and the control of a large gasification process in simultaneous channels. Contaminant escape is minimised by gasification of the in-situ coal at the equilibrium hydrostatic pressure in deeper seams (>600m), and further environmental data and trial monitoring are required for the environmental impact assessment of future schemes.

3. Scale-up to commercial UCG operation was demonstrated in the early Soviet Union UCG stations to produce gas for thermal power stations, two of which are still in operation (Uzbekistan and Siberia). More recently in the 1990s, the only scale-up activities for UCG have been the design studies in the USA (SNG Plant) and Australia (Chinchilla), but a full-scale demonstration plant will need to be built before UCG can be commercialised.

4. The European trial demonstrated that directional inseam drilling and a movable injection point (CRIP) are the key requirements for seam access and UCG process control in deep coal seams, and the study has concluded that the process can be applied satisfactorily and scaled up to UCG process well construction, although this has to be demonstrated.

Recommendations for Future Action

The DTI initiative on UCG was started in 1999 on the premise that, with the exception of directional drilling, the technology and engineering of small-scale UCG were largely solved and that trials (drilling and UCG) should be conducted in typical UK coals to demonstrate the technology in the UK. To move towards this objective, the DTI targets for UCG were identified (see Chapter 1); this work is now reaching completion, and the current activities (September 2004), which the DTI is supporting, are:

- A watching brief of overseas activities.
- Evaluation of the Firth of Forth as a potential future UCG project site. (Heriot-Watt/DTI/Scottish Enterprise/Scottish and Southern Energy plc.)
- Promotion of the study results on UCG through the DTI web site.
- Dissemination through the publication of papers and posters at relevant conferences.

This report has established that UCG-CCS is a potential future technology for the exploitation of UK coal resources, particularly for coal resources under river estuaries, and near-shore and eventually offshore coal, although concerns remain about the environmental impact of UCG, approval under the Groundwater Regulations and public perception issues. In addition, the scoping economics of UCG-CCS need refinement and offshore UCG (from platforms) requires further investigation. In short, UCG-CCS is a promising technology for the UK, although it has to be a commercial decision whether to deploy it, taking into account the planning hurdles that would need to be overcome before any project can go ahead.
The feasibility study for the Firth of Forth has the potential to become a ‘lighthouse’ project for taking this technology forward, although decisions on this will have to be taken on a commercial basis. By investigating a specific site area, the study has the potential to clarify and potentially resolve many of the outstanding environmental, planning and hydrogeological issues identified in this report. UCG-CCS has reached the stage where, ideally, an industry consortium should lead the future development of the technology, and there is probably a range of service providers (drilling, process design, mineral and hydrocarbon extraction), and equipment manufacturers (plant, power generation) which would benefit from a successful development of UCG. The Firth of Forth study is currently the leading opportunity to develop a UCG demonstrator in the UK.

UCG should be seen within the context of the Carbon Abatement Technologies Strategy that is currently being developed by the DTI. It is expected that UCG (with CCS) will be seen alongside other sustainable fossil fuel technologies such as IGCC and natural gas-fired generation with CCS. Which of these technologies prevails will very much depend on their relative commercial and technical attractiveness.