

Review of Environmental Issues of Underground Coal Gasification

Report No.
COAL R272
DTI/Pub
URN 04/1880

November 2004

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The work described in this report was carried out under contract as part of the DTI Cleaner Coal Technology Transfer Programme. The programme is managed by Future Energy Solutions. The views and judgements expressed in this report are those of the contractor and do not necessarily reflect those of the DTI or Future Energy Solutions

First published 2004

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EXECUTIVE SUMMARY

This study was initiated by the DTI Cleaner Coal Programme as part of the UK initiative on underground coal gasification (UCG). UCG has potential in the longer term to access and exploit the large coal resources of the UK, but concerns remain about the environmental impact of UCG on ground water supplies.

A review of past UCG projects indicated that the risk of contamination of groundwater through gas escape and leachate migration was the most significant environmental issue of UCG. The risks can be mitigated by the careful selection of the site and effective process control during after the gasification process has taken place.

The study has analysed the environmental process from the formation of the contaminants in the reactor, through to the eventual fate of those pollutants in the groundwater or atmosphere. Methodologies are proposed for the assessment of risks and the identification of “permanently unsuitable” (PU) groundwater areas in coal seams where UCG can take place without threatening adjacent aquifers.

Pressure control during the gasification process, to ensure that underground water flow is always towards the reactor is an effective method of contaminant control of both gaseous and liquid pollutants. When the process is finally shut down, accurate process and pressure control must continue until the reactor is stabilised and the remaining contaminants are removed.

The development of a UCG trial site would be the subject of a planning application submitted in accordance with the Town and Country Planning Act 1990. A semi-commercial operation would include electricity generation and could (if the capacity of the power plant exceeds 50 MWe) require consent from the Secretary of State for Trade and Industry under Section 36 of the Electricity Act 1989. The production of an Environmental Impact Assessment (EIA) is also likely to be required.

Both the trial and semi-commercial operation would fall under the Pollution Prevention and Control Regulations and an IPPC permit covering the ground and air emissions would be required.

A Best Practice Document has been produced for the management of the environmental issues of UCG trials and semi-commercial operations.

Likely future users of the Project results

The results of the project will primarily be of greatest use to any public or private organisations considering undertaking UCG trials within the UK.

The project results are also likely to be of interest to the many regulatory bodies responsible for the regulation of the planning, development, operation and closure of UCG developments within the UK.

Introduction to UCG

The United Kingdom (UK) has large reserves of indigenous coal, both onshore and offshore, in the southern North Sea. These have the potential to provide security of future energy supplies long after the UK's oil and natural gas reserves are exhausted. However the extraction of these coal reserves is currently problematical. Underground coal gasification (UCG) could, potentially, provide a solution.

In 1999 the Department of Trade and Industry (DTI) published Energy Paper 67 setting out the Government's policy on cleaner coal technologies research, which included the target of identifying a semi-commercial site within the UK for UCG. The UK wide search for a suitable trial site has once again highlighted the importance of environmental issues, which need to be thoroughly investigated before site work is initiated. The DTI Cleaner Coal Programme, managed by Future Energy Solutions, commissioned this project entitled 'A Review of Environmental issues of Underground Coal Gasification' to meet this objective.

Review of Previous UCG Trials

A review of previous trials indicated that most were carried out in conditions significantly different from those proposed for a UK trial. However, the review provided useful information on the nature of UCG development and the associated environmental risks, although many of these risks can be ameliorated at the depth and conditions proposed for the UK. The most relevant, and most reported, trials were those carried out in the United States of America (US) during the late 1970's and 1980's and the deep European trial at the El Tremedal site in Spain.

Previous UCG trials have shown that the potential for groundwater pollution can be a significant concern. However, these pollution events were associated with shallow reactors (such as those developed in the US) and the risks presented by a deep UK reactor are considered to be much lower.

The best evidence for this conclusion comes from a comparison of the early American trials (Hanna and Hoe Creek) with the later trials at Rocky Mountain (350m depth) and El Tremedal, Spain (550m). While, cavity concentrations are comparable, only the former showed a persistent spread of leachates into the adjacent strata.

Ground Water Mechanisms and the Nature of the Contaminants

The operation and shutdown of a gasification reactor can result in the following emissions that may cause contamination of groundwater in and around the reactor:

- escape of the product gas during operations and build up after operations have ceased;
- leaching of pyrolysis products produced by pyrolysis of the reactor walls (during and after gasification);
- leaching of inorganic contaminants from the mineral ash produced by the gasification process (within the reactor and pyrolysis zone).

Such emissions are minimised by effective process control during and following cessation of gasification.

At the high pressures and temperatures of the reactor, the main components of the product gas that pose a risk to groundwater, are sulphides chlorides, ammonia and its derivatives (hydrogen cyanide).

Geological Factors influencing the Migration of Contaminants

The risk of groundwater pollution from UCG depends almost entirely on whether the contaminants can migrate beyond the immediate reactor zone to more 'sensitive' groundwater areas. For simplicity, emissions have been separated into gas escapes and leachates although interactions between the two are also discussed where appropriate.

1. Gas Transport Mechanisms

In previous trials, transport of gases as a free phase by displacement of pore water in the rock matrix appears to be the only mechanism that would provide sufficiently rapid gas transport to cause the contamination effects that have been observed.

The gas is driven by the difference between the pressure regime in the reactor and hydrostatic conditions in the rock matrix, and the migrating gas front pushes groundwater out of fissures and fractures in strata, allowing the front of the gas body to migrate rapidly through the strata. The product gases will tend to flow upwards due to their buoyancy, irrespective of the direction of groundwater flow, and the distance that gases migrate will depend on:

- the resistance to flow of the surrounding strata
 - the continuity between the escaping gas body and the UCG reactor.
- Even in a 'worst case' scenario, gas escape is likely to be short-lived and intermittent thus limiting the distances over which the gases can move.

2. Aqueous Phase Contaminant Transport Mechanisms

The transport of aqueous phase contaminants depends on the geological setting of the gasification reactor and the hydrogeology of the area.

Simple leaching of contaminants from the reactor during operations is unlikely as hydrostatic conditions will tend to promote groundwater flow towards the reactor, but dissolved contaminants can become entrained within gas escapes. This can leave a 'deposit' of acidic, high sulphur/chlorine water containing dissolved ammonia and leached organics some distance from the reactor. During previous studies, many of these contaminants have been pulled back into the reactor at the end of the process as pressures in the reactor are lowered during venting.

Factors Influencing Contaminant Escape during Operations

The operation of the gasifier is as important as the geological factors discussed above.

Gases and pyrolysis contaminants in and around the gasification cavity should be 'contained' by groundwater if pressures within the gasification reactor are less than or equal to hydrostatic pressure (as groundwater flow will be towards the

gasification reactor). The rock mass properties of the overburden and the properties of the coal will dictate the amount of water flowing into the cavity from the fractured zone created by the caving of the reactor, along with the pressure differential (the 'driving head').

Although gas escape is unlikely to happen if the pressure gradient is towards the gasification reactor, exceptions may occur if there are any large, open faults or fissures around the gasification reactor that could cause localised dynamic reductions in hydrostatic head.

As operational pressures in the cavity are reasonably controllable, the available evidence indicates that the main form of contaminant escape during the process is likely to be associated with short-term gaseous emissions (a few days or less). Emission of aqueous phase contaminants not entrained within gas escapes beyond the immediate vicinity of the reactor is very unlikely during operations.

During the post operation phase, the dispersal of heat and potential build up of gas pressures caused by inflowing waters turning into steam are important considerations. If the reactor is not vented, then gas pressure can increase as groundwater is vaporised which can lead to cavity pressures that are greater than in-situ hydrostatic pressure. If a reactor is fully vented, then the gas pressure so induced within the reactor cannot exceed the hydrostatic pressure between the base of the production well and the surface.

Evaluation of Ground Water Risks

UCG poses a theoretical risk to ground water through both gas escapes and leachate movement (the latter may pose a pollution risk for some time after operations have ceased). The Groundwater Regulations 1998 (SI 1998 No. 2746) will require a prior investigation of the site and consideration of these risks.

Whilst some of these factors can be influenced to a certain extent, 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 of the reactor caving on local ground conditions. Site selection is therefore key to addressing concerns over groundwater pollution.

Close liaison with Regulators and conservative approaches to risk assessment will be required, due to the uncertainties over contaminant generation, persistence, and transport through the geo-sphere, and the fact that a complete understanding of the below ground environment cannot be gained without prohibitively expensive investigation techniques. However, by using appropriate desk studies, site investigation methods and hydrogeological assessment techniques it should be possible to develop a sufficiently robust risk assessment for a suitable site that will address concerns over groundwater whilst allowing for these uncertainties.

A key parameter that defines the risk in a UK context is identification of a zone of "Permanently Unsuitable" groundwater which is essentially 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'. The PU zone implies that the assessment of the pollution risk should be geared towards examining the possibility that significant quantities of contaminants will migrate beyond this zone to overlying (or even underlying) aquifers.

Planning and Regulatory Issues

Planning Requirements

A UCG trial site would require a planning application submitted in accordance with the Town and Country Planning Act 1990. A trial UCG site is likely to be considered as a stand-alone mining operation, but a semi-commercial operation would be treated as both a mining project and an industrial process. If the capacity does not exceed 50 MWe the planning application would be made to cover the two operations (mining and industrial), but greater than 50 MWe would require the consent from the Secretary of State for Trade and Industry under Section 36 of the Electricity Act 1989 and a separate applications would need to be made for the mining and industrial activity. The existing Mineral Planning Guidance Notes (MPG1 & MPG2) would be applied to UCG and for the future, a policy statement (MPS2) covering environmental and mitigation of mineral workings has been issued (February 2003) for consultation.

The trial and semi-commercial operation both fall within Schedule 2 of the Town and Country Planning (Environmental Impact Assessment) Regulations 1999 and the production of an Environmental Impact Assessment (EIA) is not mandatory. Having regard to the characteristics of UCG and its potential environmental effects however, it is highly probable that the determining planning authority would request that a formal EIA be carried out for both a trial and a semi-commercial operation. The contents of the EIA are discussed in the UCG Best Practice Document, prepared as part of this study.¹

IPPC Regulations and other EU Directives

The UCG process, for both the trial and semi-commercial operation would be covered under the Pollution Prevention and Control Regulations 2000 – (PPC Regs 2000(England and Wales) or PPC Regs 2000(Scotland) as appropriate) and UCG, like all gasification processes will require, an IPPC permit from the relevant Environment Agency. IPPC requires the application and use of Best Available Practice (BAT) for all emissions and detailed technical guidance² for gasification is in preparation.

The EU IPPC Directive contains a research and development (R&D) exemption clause that was not fully implemented but consultation is currently being undertaken across Europe. If the PPC Regulations 2000 and the PPC Regulations (Scotland) 2000 were to be modified to implement the R&D exemption, then the trial might be exempt from the full requirements of IPPC.

¹ UCG Best Practice to be published as part of the current Contract.

² EU BAT Reference Document known as BREF

Groundwater Regulations, which are also part of the IPPC permit process, allow exemptions for pollutants like phenols and heavy metals (List 1 & List II substances) provided the groundwater is permanently unsuitable and the substances cannot reach other aquatic systems. The definition of this PU zone is a key parameter in the site risk assessment. Other parts of the same regulations require a satisfactory monitoring regime.

In addition to the above planning and pollution regulations, UCG would have to comply with Control of Major Accident Hazards (COMAH) Regulations 1999, Air Quality Regulations and various 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 an Exploration Licence, an Operational Licence to work the coal and a Leasehold Interest in the coal from the Coal Authority. An Access Agreement from the Coal Authority may also be necessary to pass through other seams. In addition, a Surface Access Agreement would be required from the landowner and it would be necessary to sign the Interaction Agreement. It is currently uncertain as to whether a Petroleum Exploration and Development Licence would be required.

Consultation Process

A consultation process with UK Government likely to have a Regulatory Involvement with UCG was undertaken. It took the form initially of a consultation document, which was made available to Central and Regional Government for comment. This was followed up by a Consultation workshop (September 9th 2003) to which all the respondents and non Government Organisations (NGO's) were invited. A firm view developed from the consultation that a semi-commercial UCG project, because of its novel nature and being a "departure" from the development plan, is likely to be called in by the Secretary of State.

Air Emissions

An evaluation of ground level pollutant concentrations resulting from future UCG trial and semi-commercial operations was carried out. For assessment purposes, it was assumed that the UCG trial reactor would have a maximum gas production rate of 400 tonnes per day and that semi-commercial operation will generate up to 100 MWe. These notional designs were intended to give reasonable estimates of the effects on air quality.

It is anticipated that the UCG trial reactor of short duration would not require the product gas to be treated prior to co-firing with natural gas in a combustion unit. In this case, and under assumed discharge conditions, the ambient air quality criteria around the test site would be met by discharge into a stack of about 26m. The semi-commercial plant will require facilities for hydrogen sulphide removal in the product gas stream, and modelled concentrations oxides of nitrogen and sulphur dioxide were a small fraction of the air quality objectives. Site-specific dispersion modelling of this type is recommended.

CO2 and Greenhouse Gas Emissions Trading

In April 2002, the Government introduced the voluntary UK Emissions Trading Scheme in order to encourage participants to reduce emissions of greenhouse gases and the EU Directive on Greenhouse Gas Emissions will come into force in 2005 for all power plants greater than 20 MWt. The semi-commercial operation is within the remit of the Directive, and would require a permit and verification of emissions through monitoring.

CO2 capture from UCG product gas is technically feasible using current separation technology, and the high pressure makes it potentially more economic than capture from other coal (or gas) fired plant. Efficiency and cost penalties result from CO2 capture, but given an appropriate emissions trading regime, the option is likely to be considered for UCG in the future.

Conclusions to this study

1. Overseas trials have shown that UCG can pose a potentially significant risk to groundwater when the trial is at shallow depth and management of the process has been deficient. For a suitable deep UK site, the risk to water resources such as major overlying aquifers is likely to be very low.
2. UK legislation (based on EU Directives) normally prohibits the release of contaminants produced to groundwater, but exemptions are permitted when the groundwater is permanently unsuitable (PU) and it can be proven that transfer to upper aquifers will not take place.
3. Gas and contaminant escapes from the reactor can be minimised by operating below hydrostatic pressure.
4. Site selection and investigation will require a risk-based approach to demonstrate that there is a negligible risk of groundwater pollution. The assessment will have to account of the potential risk of short-term gas losses during operations and longer-term leachate issues. The effect of reactor caving on strata relaxation and increased transport paths will need to be assessed.
5. As well as suitable site selection, the three main mitigation measures for UCG are:
 - Using operational monitoring systems that can detect gas losses and ensure that reactor pressures are maintained below hydrostatic;
 - Ensuring that wells and boreholes used in the process are adequately sealed.
 - Maintaining a 'cone of depression' in the groundwater around the reactor.
 - Flushing and treatment of caved reactor water post operations may also help mitigation by removing contaminants
6. A semi-commercial UCG project will almost certainly require an Environmental Impact Assessment and there is a high probability that the project will be called in by the Secretary of State as a "departure" from the development plan.
7. Development of the trial site for UCG would be considered as a mining operation in any planning application submitted under the Town and Country Planning Act 1990, while semi-commercial UCG operation with electricity generation would

have to be assessed separately as both an industrial process and a mining operation.

8. UCG process, for both the trial and semi-commercial operation would fall under the PPC Regulations 2000 and require an IPPC permit to cover the ground and air emissions would be required. In addition, the semi-commercial operation would fall under the remit of the European Commission Directive on greenhouse gas emissions trading.
9. UCG will need to be licensed by the Coal Authority and hold a Surface Access Agreement from the landowner. It is currently uncertain as to whether a Petroleum Exploration and Development License would be required.

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1. INTRODUCTION

The United Kingdom (UK) has large reserves of indigenous coal, both onshore and offshore, in the southern North Sea. These have the potential to provide security of future energy supplies long after the UK's oil and natural gas reserves are exhausted. However, the extraction of these coal reserves is currently problematic. Traditional mining methods are not suited to offshore working, whilst onshore the development and infrastructure costs of new mines can render exploitation of reserves uneconomical.

Underground coal gasification (UCG) could, potentially, provide a solution to both of these problems. UCG is a method of converting un-worked coal, deep underground, into a combustible gas which can be used for industrial heating, power generation, or the manufacture of hydrogen, synthetic natural gas or other chemicals. It has the potential to provide a source of energy derived from coal seams where traditional mining methods are impossible or uneconomic.

In 1999 the DTI published Energy Paper 67 entitled 'Cleaner Coal Technologies Future Plans for Research and Development, Technology Transfer and Export Promotion'. This paper set out the Government's policy on CCT research, their development and demonstration. CCT are those technologies, most commonly associated with the use of coal for power generation, that improve the environmental acceptability of coal extraction, preparation and utilisation. They include methods of extracting the energy from coal in a less environmentally damaging way through the use of UCG.

In the UCG process the combustible gas is produced by the partial, in-situ combustion of an underground coal seam by a mixture of oxygen (or oxygen enriched air) and water, the reactants. The oxygen (or oxygen enriched air) and water are injected from the surface via an injection well, and the resulting coal gasification occurs in a chamber, the gasification reactor, within the coal seam. The product gas is extracted via a production well. Together, the injection well and injection facilities, the production well and production facilities and their associated gasification reactor comprise one UCG module.

The development of the gasification reactor is initiated at a safe distance from the production well and the reactor increases in volume as the gasification process develops. Ignition of the coal is accomplished by the injection (via the injection well) of oxygen gas (or oxygen enriched air) and a means of ignition of the coal (eg a hypergolic compound). The gasification process takes place mainly at the outer surface of the reactor, with the thermally altered coal collapsing into the reactor and exposing new areas of un-reacted coal. As the productivity of the initial zone of gasification declines over time, new injection points are induced at one or more locations towards the injection well, and ultimately at the injection point itself. As the volume of the reactor increases,

the overlying strata (the overburden) may collapse. The extent of the collapse is dependent upon the nature of the overburden.

The rate of gasification is dependent upon the rate of flow of oxygen (or oxygen enriched air) to the reactor, whilst the thermochemical efficiency of the process (ie the proportion of useful products in the product gas) is dependent upon the reactant (oxygen/water) ratio. These relationships allow the gasification process to be controlled at the surface.

In certain instances, an excess of water (above the thermochemical optimum) needs to be pumped from the surface into the reactor to compensate for any deficiency in the reaction zone (the area within the reactor where the gasification of the coal is actually occurring). Alternatively, in instances where the water content of the coal or the influx of groundwater to the reactor is significant, it is necessary to compensate for these underground water sources by extracting water from the reactor and pumping it to the surface. These factors will be determined by the nature of the coal seam and its surrounding strata and will, therefore, vary from location to location.

It should be noted that it is not possible for the combustion or gasification of coal within the coal seam to continue without the supply of oxygen. The flow of reactants to the reactor is achieved by actively pumping against a considerable back pressure. If there is any interruption to this supply, the underground gasification process will cease hence there is no possibility of the gasification process 'running-away'. High pressure nitrogen gas may be used to purge the reactor or the injection or production wells of product gas as a means of stopping combustion of the gas.

At the production wellhead, the product gas is predominantly a mixture of carbon monoxide (CO), hydrogen (H₂), carbon dioxide (CO₂), methane (CH₄), and water vapour, with lower levels of other gases (eg hydrogen sulphide, ammonia) and traces of a wide range of organic compounds (eg phenols, organic acids etc.).

To protect the integrity of the walls of the production well, it is necessary to inject water into the bottom of it (a process known as 'sparging') to limit the temperature of the product gas entering it (usually to below 350°C). The sparge water returns to surface as steam entrained in the product gas.

Once at the surface, UCG product gas needs to be treated to render it useful, either as a fuel or as a chemical feed stock. Depending upon its ultimate use, treatment may involve de-watering and dehydration, the removal of CO₂, compounds of sulphur and other impurities. The treatment of the product gas may result in the production of a number of waste streams that will require treatment, re-use or disposal.

Many potential future uses of UCG product gas will require the CO₂ to be separated off. Depending upon its economic viability, the separated CO₂ may be put to productive use elsewhere or disposed of by emission into the atmosphere. One possible future use of CO₂ gas arising from UCG may be its use in enhanced coal bed methane (CBM) extraction. Enhanced CBM extraction involves pumping CO₂ into CH₄ bearing coal seams in order to displace the CH₄ so that it can be extracted. The CO₂ gas remains 'sequestered' within the coal seam.

At the end of the operational phase, the gasification process is stopped by halting the injection of reactants. The gasification module is then depressurised by gradually releasing the gas from the system (a process known as venting).

The basic feasibility of UCG has been proven in previous trials in the United States of America (USA), China and, more recently, Europe and Australia. The process was used for heating and power production for many years in the countries of the former Soviet Union. The approach adopted by these UCG trials and operations has varied, but principally it has focused on the exploitation of shallow coal seams. However, new technologies from the exploration industry, tested in recent trials, would seem to indicate that UCG in deep coal seams has advantages as a clean coal process, which may be unmatched by other methods of coal exploitation.

It is the Government's policy to encourage the development of cleaner coal technologies (CCT). The extraction of energy from the vast UK coal reserves could reduce the UK's future dependence on imported fuels and may also help the UK retain its current position as a net exporter of energy. In pursuit of this policy, between 1992 and 1999, the UK Department of Trade and Industry (DTI) part-sponsored a European Union (EU) trial into the feasibility of UCG at depths typical of European coal. From this trial it was concluded that the UCG process has the potential for application to the UK deep coal reserves.

The technology targets that the UCG programme will address over the next six years are as follows:

- investigate the accuracy and repeatability of in-seam drilling;
- examine the implications of burning UCG gas in gas turbines;
- estimate the landward coal reserves for UCG;
- identify a semi-commercial site within the UK;
- establish cost parameters for the process to be competitive against natural gas; and
- carry out a pre-feasibility study of offshore exploitation of UCG.

Meeting these targets will, in part, involve an initial trial to evaluate practical aspects of the technology (the proposed trial will build upon the EU trial

undertaken in Spain) and a second, semi-commercial operation to evaluate the economics of the process. It is envisaged that the trial will take around five years to complete from initial construction work through to decommissioning and site restoration and will involve gasification for around nine months. The semi-commercial operation is expected to be in operation for up to 20 years.

Major UK consultants have been involved in the UK wide search for a suitable UCG trial site. A preliminary review has been undertaken of geological setting, coal requirements, the presence of aquifers, and planning and surface land requirements. A number of suitable coalfield prospects have been identified throughout the UK. These areas will now be subject to more detailed investigation, including possible borehole and site investigation.

The process of site selection, once again, highlighted the importance of environmental issues. Therefore the project entitled 'A Review of Environmental Issues of Underground Coal Gasification' was commissioned by the DTI through Future Energy Solutions. The objectives of this project were to:

- review critically relevant environmental experience from previous UCG trials;
- identify UK environmental legislation applicable to UCG; and
- develop an environmental best practice manual for both trial and semi-commercial operations.

This document provides the final report for the project and addresses the following subject areas:

- technical review of environmental aspects of previous UCG trials;
- assessment of technical factors influencing the impact of UCG on groundwater quality;
- evaluation of the risks to groundwater;
- surface water issues;
- CO₂ sequestration;
- UK environmental regulatory regime for UCG;
- air and global emission issues;
- best practice; and
- conclusions.

In addition to the final report, a Best Practice Guidance Document has been produced for use in the assessment of environmental impacts of UCG sites. The Guidance Document is referred to where applicable in this report.

Atkins have prepared this report on the basis of information concerning UCG known at the time. In the event of changes in best practice, processes or legislation affecting UCG, and in any case following any UCG trials, this report should be reviewed. Atkins accept no liability for the use of this report in circumstances that do not conform to this requirement.

2. TECHNICAL REVIEW OF ENVIRONMENTAL ASPECTS OF PREVIOUS UCG TRIALS

UCG trials and projects have been conducted by various countries since the mid-20th century. The majority of these trials were operated in the following conditions:

- shallow coal seams (< 200 m depth);
- thick and nearly flat coal seams (dip angle < 30°); and
- low rank coal (lignite or sub-bituminous coal).

Most previous trials are therefore significantly different from the conditions proposed for a UK trial. However, an elemental review of previous trials has provided useful information on the nature of UCG development and the associated environmental risks at the depth and conditions proposed for the UK. This information has been used in later sections to assess the technical factors that influence the environmental impacts of the UCG process in the UK setting.

2.1 RELEVANCE OF PREVIOUS TRIALS

2.1.1 Countries of the Former Soviet Union

Initially, the Soviet Union's investigations into UCG far exceeded the efforts of all other nations. A summary of the most relevant UCG trials in the former Soviet Union is presented in Table 2.1. In the early 1960's, five 'Podzemgaz' experimental UCG stations were in operation, distributing their gas locally for industrial use. Two stations are still operational: (i) the Angren station in Uzbekistan, Central Asia using brown coal and (ii) the Juschno-Abinsk station in Siberia using hard coal. It is reported that a total of some 15 million tonnes of coal have been gasified underground in the former Soviet Union.

Site name	Podmoskovna	Lisichansk	Schatsky	Juschno-Abinsk in Siberia	Angren in Uzbekistan
Year of gasification	1947-62	1948-62	1965-74	from 1955	from 1962
Depth ⁽¹⁾	Shallow	Shallow	Shallow	Shallow	Shallow
Duration (days)	N.A.	N.A.	N.A.	N.A.	N.A.
Tonnes gasified	In total, some 15 million tonnes				
Seam Dip ⁽²⁾	Nearly horizontal	Intermediate	Nearly horizontal	Steeply	Nearly horizontal
Well configuration	Linked vertical wells combined with underground works	Linked vertical wells combined with underground works	Linked vertical wells combined with underground works	In-seam wells combined with vertical wells	Linked vertical wells combined with underground works
Linking method	Reverse combustion, hydraulic fracturing and/or in-seam drilling	Reverse combustion, hydraulic fracturing and/or in-seam drilling	Reverse combustion, hydraulic fracturing and/or in-seam drilling	Reverse combustion, hydraulic fracturing and/or in-seam drilling	Reverse combustion, hydraulic fracturing and/or in-seam drilling
Coal Rank ⁽³⁾	Low	Intermediate	Low	Low/intermediate	Low
Gasification agents	Air	Air/O ₂	Air	Air	Air
Adjacent strata characteristics	N.A.	N.A.	N.A.	N.A.	Coaly shale
Gas losses ⁽⁴⁾	High	High	High	High	High
Availability of environmental impact data	N.A.	Low	N.A.	Low	N.A.

⁽¹⁾ *Shallow: 0 - 200m; Intermediate: 200 - 500; Great: >500 m*

⁽²⁾ *Nearly horizontal: 0° - 30°; Intermediate: 30° - 60°; Steeply: 60° - 90°*

⁽³⁾ *Low: lignite to sub-bituminous; Medium: bituminous; High: semi-anthracite to anthracite*

⁽⁴⁾ *Low: 0 - 5%; Medium: 5 - 10 %; High: >10 %*

Table 2.1 - Relevant UCG Trials in Former Soviet Union

2.1.2 Europe

Information on the relevant European UCG trials is presented in Table 2.2. Initial trials with UCG were made in the UK at Newman Spinney in 1949 and in the 1950's. Smaller scale UCG trials were also conducted by other European countries at this time. The most significant being those at Bois-la-Dame (Belgium, 1948) and Djérada (by France in Morocco, 1950-1955). All these trials were operated at shallow depth (less than 100 m depth) and in thin coal seams, generally from an existing underground mining network. Although gasification during these trials was successful and provided useful results, the work was abandoned at this time on economic grounds. Important gas losses were recorded during these early UCG trials.

In Europe, the majority of the coal resources are deep and of medium to high rank Carboniferous coals. Techniques for the underground gasification of deep seams are less advanced than those for shallow seams. Initial field trials were conducted in France at Bruay-en-Artois (1981) and at Haute-Deule (1985-1986) to test the reverse combustion technique at great depth and in high rank coals. The poor results recorded during these linking trials indicated the difficulties in using the reverse combustion technique and the linked vertical wells (LVW) concept at great depth.

During the Thulin field trial (a Belgo-German collaboration, Belgium, 1981-1988), which also started with the same concept of reverse combustion and vertical well linking, it was decided to apply for the first time the directional drilling technique in preparation of an underground reactor at great depth. A small underground reactor was operated for the first time at high pressure (more than 100 bar) and at great depth (~ 860 m) for a period of some months. The trial had only limited success, but proved that UCG was technically feasible in deep, high rank coal.

In April 1988, following these first promising results at great depth and with encouragement from the Commission of the European Communities (CEC), six European countries formed the European Working Group on UCG. The Member States represented in the group being Belgium, the Federal Republic of Germany, France, the Netherlands, Spain and the UK. Based on the report conclusions presented to CEC in April 1989, a first trial under the framework of an European collaboration was started in Spain at the El Tremedal site. Organisations from Spain, Belgium and the UK formed Underground Gasification Europe (UGE), an European Economic Interest Grouping (EEIG) to undertake the works.

Site name	UK	France	Belgium		Spain
	Newman Spinney series	Djérada (in Morocco)	Bois-la-Dame	Thulin (with Germany)	El Tremedal (with Belgium and UK)
Year of gasification	1949 - 1959	1950 - 1955	1948	1986-1987	1997
Depth ⁽¹⁾	Shallow	Shallow	Shallow	Great	Great
Duration (days)	N.A.	N.A.	N.A.	67	12
Tonnes gasified	N.A.	N.A.	N.A.	11	240
Seam Dip ⁽²⁾	Nearly horizontal	Steeply	Steeply	Nearly horizontal	Nearly horizontal
Well configuration	Linked vertical wells combined with in-seam drilling from underground works	In-seam wells from surface and underground works	In-seam wells from surface and underground works	Deviated in-seam injection well Vertical production well	Deviated in-seam injection well Vertical production well
Linking method	Reverse combustion and in-seam linking	Reverse combustion and in-seam linking	Reverse combustion and in-seam linking	In-seam drilling Reverse combustion (final)	In-seam drilling Hydraulic breakthrough (final)
Coal Rank ⁽³⁾	Low	High	High	High	Low
Gasification agents	Air	Air	Air	1) Air 2) O ₂ /water	O ₂ plus natural water influx
Adjacent strata characteristics	N.A.	N.A.	N.A.	Shale	Clayey sand
Gas losses ⁽⁴⁾	High	High	High	High	High
Availability of environmental impact data	N.A.	N.A.	N.A.	Low	Low

⁽¹⁾ *Shallow: 0 - 200m; Intermediate: 200 - 500; Great: >500 m*

⁽²⁾ *Nearly horizontal: 0° - 30°; Intermediate: 30° - 60°; Steeply: 60° - 90°*

⁽³⁾ *Low: lignite to sub-bituminous; Medium: bituminous; High: semi-anthracite to anthracite*

⁽⁴⁾ *Low: 0 - 5%; Medium: 5 - 10 %; High: >10 %*

Table 2.2 - Relevant UCG trials in Europe

The El Tremedal UCG trial was the most successful UCG field trial performed in the world to date at great depth. Access to the thin sub-bituminous coal seam situated at an average depth of 560 m was provided by an in-seam deviated well. During the gasification operation, two controlled retraction injection point (CRIP) manoeuvres were realised successfully and approximately 240 tonnes of coal were gasified. The underground reactor was

operated at approximately 52 bar with the sole injection of oxygen (no water). The water influx from overlying strata was sufficient to permit gasification.

2.1.3 USA

In the USA, UCG developments focussed principally on shallow and relatively thick sub-bituminous coal seams. The most successful trials in the USA are the Rawlins trial (1979-1981) for steeply dipping coal seams and the Rocky Mountain 1 (RM1) trial (1987-1988) for the near horizontal coal seams. The success of these trials resulted principally from the use of modern directional drilling techniques, gasification with oxygen and steam, and, in the case of RM1, the use of the CRIP concept developed in a previous UCG trial in Centralia (Tono 1 trial), Washington (1983-84).

The RM1 UCG trial is certainly the most documented and significant UCG trial conducted in USA to date in a shallow (~ 100 m depth) near horizontal coal seam. The total amount of coal gasified in both modules was estimated to be over 14,000 tonnes. The trial objectives were (i) to compare the Extended Linked Well (ELW) concept (an improvement on the LVW concept by using deviated in-seam drilling in place of reverse combustion) with the CRIP concept and (ii) to develop methods to reduce and mitigate environmental impacts to groundwater from UCG operations (the Clean Cavern Concept).

The RM1 UCG trial, situated on a site near Hanna in Wyoming, followed a series of UCG trials (Hanna UCG trial series, from 1973 to 1979) conducted by the Laramie Energy Technology Centre where the LVW concept with reverse combustion linkage and forward gasification with air was previously tested.

In parallel to the Hanna UCG series, a series of UCG trials were also conducted by the Lawrence Livermore National Laboratory (LLNL) at Hoe Creek from 1976 to 1979. Hoe Creek I tested explosive fracturing as a permeability enhancement of the LVW concept. After linking, the coal seam was ignited with air and a low quality gas was produced over approximately 11 days. Subsequently, the Hoe Creek II trial was conducted to test reverse combustion linking, and Hoe Creek III was conducted to test a horizontally-drilled linking finalised by reverse combustion. Both trials were then used to experiment with gasification using air and oxygen/steam. Significant subsidence and groundwater contamination were recorded during and after these trials. The subsidence resulted from the void created during gasification and propagated to the surface through the weakly consolidated overburden. The principal contaminants introduced into the groundwater were volatile and semi-volatile organics where benzene was the contaminant of highest concentration and persistence.

The LLNL developed the concept of CRIP as an improvement of the conventional LVW concept taken from the Russian experience in UCG. The CRIP concept was designed to avoid the upward development of the cavity observed in all previous near-horizontal UCG trials (Hanna and Hoe Creek

series). The CRIP concept was first tested during the Tono 1 trial in Centralia, Washington State. The Tono 1 UCG trial followed a series of small-scale in-situ experiments named 'Large Block Tests' that were conducted at the same site to understand the cavity growth mechanisms.

UCG in steeply dipping beds was also developed in Russia and operated to produce fuels for local industrial application. UCG in steeply dipping beds is in fact comparable to fixed bed surface gasification (the Lurgi gasifier for example). From 1979 to 1981, Gulf Research and Development Company adapted this technique and made two steeply dipping UCG tests at a site near Rawlins, Wyoming. During the first, test air injection was used to produce a low heating value gas. The second test at Rawlins conducted at a bigger scale achieved excellent results. The 65-day test utilised steam and oxygen injection and gasified approximately 7,600 tonnes of coal. During this trial, the oxygen utilisation was considered superior to surface gasifiers and an excellent control of the process was obtained with a wide range of process conditions (steam/oxygen ratio and counter-pressure).

The main characteristics of these trials sponsored by US government are summarised in Table 2.3. In addition to the UCG trials sponsored by the US government, several trials were conducted by private industry during the same period but very little publicly available information exists on these trials.

Site parameters	Hanna series (1 to 4)	Hoe Creek series (1 to 3)	Pricetown	Rawlins series (1 to 2)	Centralia - Large block tests - Tono 1 trial	Rocky Mountain I
Year of gasification	1) 1973-74 2) 1975-76 3) 1977 4) 1978-79	1) 1976 2) 1977 3) 1979	1979	1) 1979 2) 1981	1983-84	1987-88
Depth ⁽¹⁾	Shallow	Shallow	Intermediate	Shallow	Shallow	Shallow
Duration (days)	1) 180 2) 101 3) 38 4) 24	1) 11 2) 59 3) 47	12	1) 35 2) 65	29	93 (CRIP) 57 (ELW)
Tonnes gasified	1) 3,600 2) 7,250 3) 2,600 4) 1,350	1) 120 2) 2,250 3) 3,550	320	1) 1,100 2) 7,600	1,800	10,000 (CRIP) 4,150 (ELW)
Seam Dip ⁽²⁾	Nearly horizontal	Nearly horizontal	Nearly horizontal	Steeply	Nearly horizontal	Nearly horizontal

Site parameters	Hanna series (1 to 4)	Hoe Creek series (1 to 3)	Pricetown	Rawlins series (1 to 2)	Centralia - Large block tests - Tono 1 trial	Rocky Mountain I
Well configuration	Linked vertical wells	Linked vertical wells	Linked vertical wells	In-seam production well Vertical injection wells	Slant in-seam wells Vertical wells for final linking	<u>CRIP Module</u> Deviated in-seam wells <u>ELW Module</u> Linked vertical wells
Linking method	Reverse combustion	1)Explosive fracturing 2)Reverse combustion 3)horizontally-drilled well combined with reverse combustion	Reverse combustion	In-seam drilling Reverse combustion (final)	In-seam drilling Reverse combustion (final)	Deviated in-seam drilling Reverse combustion (final)
Coal Rank ⁽³⁾	Low	Low	Intermediate	Low	Low	Low
Gasification agents	Air	1and 2) Air 2) O ₂ /steam	Air	1) Air 2) O ₂ /steam	O ₂ /steam	O ₂ /steam
Adjacent strata characteristics	Fine-grained sandstones with some claystones	Loosely consolidated sandstone	Mudstone/shale	N.A.	N.A.	Fine-grained sandstones with some claystones
Gas losses ⁽⁴⁾	Low	High	Medium	Low	Medium	Medium
Availability of environmental impact data	Medium	Medium	Low	Medium	Medium	high

⁽¹⁾ *Shallow: 0 - 200m; Intermediate: 200 - 500; Great: >500 m*

⁽²⁾ *Nearly horizontal: 0°- 30°; Intermediate: 30° - 60°; Steeply: 60° - 90°*

⁽³⁾ *Low: lignite to sub-bituminous; Medium: bituminous; High: semi-anthracite to anthracite*

⁽⁴⁾ *Low: 0- 5%; Medium: 5 – 10 %; High: >10 %*

Table 2.3 - Relevant UCG Trials in USA (sponsored by US Government)

2.1.4 New Zealand, Australia and China

A small scale UCG trial was operated in 1994 in the Huntly Coal Basin, New Zealand. The test was carried out over a period of 13 days and approximately 80 tonnes of coal were gasified using the CRIP technique. The well configuration was based on the CRIP module configuration developed during the RM1 trial. No data on the environmental impact of this trial are available.

More recently, a large scale UCG trial involving the technology developed in Uzbekistan has been operated from 1999 to 2002 in Chinchilla, Australia. The UCG facility at Chinchilla used air injection, and produced low calorific value gas at a pressure of 10 bar. The trial included nine vertical process wells and gas has been produced from a 10 m thick coal seam at a depth of about 140 m. During operations, approximately 32,000 tonnes of coal have been gasified. No information is currently available concerning the linking method applied and the environmental impact (water quality and subsidence).

China has also undertaken several UCG trials over the last ten years and at least two are currently in operation. The work uses abandoned galleries of disused coal mines for gasification. Vertical boreholes are drilled into the gallery to act as injection and production wells. A system of alternating air and steam injection, or a classical air gasification, is used to gasify the coal. Very little information exists concerning the environmental impacts of these trials. Table 2.4 presents the main characteristics of the Australasian and Chinese trials.

A technical review of the gasifier configuration is presented in Appendix A. The parameter with the greatest influence on UCG operational and environmental performance is depth. Its influence is considered in the following section.

Site parameters	China				New Zealand Huntly trial	Australia Chinchilla trial
	Xinhe mine, Xuzhou	Liuzhang mine Tanshan	Yilan, Heilongjiang	Yima Hebi and Xinmi in Henan		
Year of gasification	1994	1996	1998	2000	1994	1999-2002
Depth ⁽¹⁾	Shallow	Shallow	Shallow	Shallow	Shallow	Shallow
Duration (days)	N.A.	N.A.	N.A.	N.A.	13	900
Tonnes gasified	N.A.	N.A.	N.A.	N.A.	80	32,000
Seam Dip ⁽²⁾	Nearly horizontal	Nearly horizontal	Nearly horizontal	Nearly horizontal	Nearly horizontal	Nearly horizontal
Well configuration	Linked vertical wells combined with underground works	Linked vertical wells combined with underground works	Linked vertical wells combined with underground works	Linked vertical wells combined with underground works	Deviated in-seam wells	Linked vertical wells
Linking method	N.A.	N.A.	N.A.	N.A.	Deviated in-seam drilling	N.A.
Coal Rank ⁽³⁾	N.A.	N.A.	N.A.	N.A.	Low	Low
Gasification agents	Alternating air and steam	Alternating air and steam	Air	Air	O ₂ /steam	Air
Adjacent strata characteristics	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Gas losses ⁽⁴⁾	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Availability of environmental impact data	N.A.	N.A.	N.A.	N.A.	N.A.	Low.

⁽¹⁾ *Shallow: 0 - 200m; Intermediate: 200 - 500; Great: >500 m*

⁽²⁾ *Nearly horizontal: 0° - 30°; Intermediate: 30° - 60°; Steeply: 60° - 90°*

⁽³⁾ *Low: lignite to sub-bituminous; Medium: bituminous; High: semi-anthracite to anthracite*

⁽⁴⁾ *Low: 0- 5%; Medium: 5 – 10 %; High: >10 %*

Table 2.4 - Relevant UCG Trials in China, New-Zealand and Australia

2.2 EFFECT OF DEPTH ON UCG PERFORMANCE

UK proposals for UCG are based on the gasification of relatively thin sub-horizontal seams at a depth of between 600 m to 1200 m using the directional drilling technique to prepare the UCG configuration, and the use of oxygen/water as gasifying agents.

As indicated in the preceding section, the majority of previous UCG trials have been conducted at shallow depth (less than 200 m). One trial has been operated at intermediate depth (Pricetown, 1984) and only two trials have been operated at great depth (Thulin, 1986-87 and El Tremedal, 1997). This section explores the significant influence that depth has on the UCG process, and the environmental consequences, including:

- process control;
- the gasification pressure;
- the compaction of the reactor; and
- the permeability of the coal and adjacent strata.

2.2.1 Process Control

Coal can be neither gasified nor burned in the absence of oxygen and, in deep coal suitable for UCG, the only available oxygen is that introduced via the injection well. Hence, when oxygen injection is terminated, gasification ceases and the system progressively cools down. There is therefore no risk of the gasification process 'running out of control'.

This is not the case when UCG is carried out at very shallow depths, when fracturing and even caving can extend to the surface, permitting air access to the gasifier which could sustain gasification or combustion in the absence of oxygen injection.

2.2.2 Gasification Pressure

UCG has been operated in equilibrium with, or just below, hydrostatic pressure to inhibit flow exchanges with the surrounding strata. Consequently, most UCG trials realised in shallow coal seams were generally operated at pressures below 10 bar. The pressures of the UCG trials operated at greater depth were respectively 50 bar (Pricetown), 58 bar (El Tremedal) and 200 bar (Thulin).

The influence of the gas pressure within the in-situ reactor is profound. Gasification at higher pressure (assuming no change in temperature) will produce more CO₂ and hydrocarbons (CH₄ etc) and less synthesis gases (CO plus H₂). In addition, increasing pressure has the following effects:

- the CV of the product gas is increased, as is the gasification;
- the mass of coal gasified per unit mass of oxygen injected increases;
- the proportional heat losses to strata are reduced, approximately in inverse proportion to pressure;

- higher temperatures are easier to maintain, and the concentration of gaseous pollutants in the product gas is minimised at higher temperatures;
- the maximum possible rate of coal gasification is proportional to the in-situ pressure within the reactor;
- the mass transfer capability is enhanced, and a better exchange is therefore established between the combustion zone (high temperature) and the coal face (low temperature) consequently decreasing the risk of oxygen by-pass;
- the transit time and the volume of gas in the gasifier will also be increased proportionally to the pressure; and
- the condensation temperatures of steam and heavy hydrocarbons will be considerably increased (the condensation temperature of steam at 100 bar or 1000 m depth equivalent is 311°C). Consequently, the risk of steam and heavy hydrocarbon condensation is increased at great depth in low temperature regions of the gasifier and in the production well.

These effects derive from a combination of several physical and chemical factors which are discussed in Appendix B.

2.2.3 Gasifier Compaction

Compaction of the caved strata within the gasifier will generally increase with depth due to the increased strata pressure. This will increase the efficiency of the gasifier by improving the gas flow characteristics, increasing the radius of the gasifier and reducing the potential for oxygen by-pass. The influence of caved strata compaction on reactor development is discussed further in Appendix C.

Increasing depth therefore offers the prospect of developing gasifiers that are both long and wide (with respect to seam thickness) from a single pair of boreholes. Environmentally this also means that the volume of coal gasified is large with respect to the zone of pyrolysed char around the periphery of the reactor (as seen in plan). Since this zone is the origin of organic pollutants (as discussed later), the development of large reactors minimises the production of such pollutants per unit of (chemical) energy produced.

2.2.4 Permeability

Although the permeability of coal within the abutment zone around the sides of the gasifier will be enhanced by the fracturing induced by the increased differential stress, the permeability of the coal and adjacent strata beyond the immediate vicinity of the gasifier has been shown to decrease with depth, reducing the potential for significant movement of contaminants beyond the reactor.

2.3 REVIEW OF GROUNDWATER IMPACTS FROM RELEVANT TRIALS

This section provides a detailed analysis of the previous trials where relevant data and conceptual mechanisms relevant to groundwater pollution were gathered for this study. The various tests have been collated into the general 'themes' of:

- formation and nature of contaminants;
- groundwater pollution events and transmission mechanisms; and
- groundwater contaminant attenuation and remediation.

2.3.1 Formation and Nature of Contaminants

Understanding of the generation of potential groundwater contaminants was developed during the USA trials, particularly at Tono 1, Hoe Creek, Hanna and the RM1 tests. The main contaminants identified were:

- organic contaminants introduced directly by condensation of pyrolysis products, which include colloidal tars and phenols;
- inorganic constituents such as sulphates, boron and total dissolved solids (TDS), caused by leaching of ash and thermally affected overburden; and
- soluble gases such as ammonia and hydrogen sulphide were also found in UCG affected groundwater.

Measurements and experiments were carried out for the Hoe Creek tests on the nature of the organic contaminants in the pyrolysis zone, largely due to concerns over the 'regenerating' nature of the contamination (Wang and Mead, date unknown). This was thought to be caused by the fact that tars etc caused by pyrolysis had become entrained within the coal cleats and was slowly leaching into groundwater (so called 'coal-coating'). The absorptive capabilities of coal are thought to be much less in the field than in laboratory studies. The reasons for this are thought to be complex, but are largely to do with the domination of fissure flow in the coal as opposed to flow through matrices. However, field results suggested that attenuation through coal adsorption contributed to the reductions encountered after a few years.

For organic contaminants, studies carried out after the Tono 1 test showed that the low molecular weight phenolic compounds are the least likely to be adsorbed by coal and high molecular weight polynuclear aromatic hydrocarbons (PAHs) exhibit the highest adsorption capacity (Brimhall, 1986). This may explain why only benzene and phenols were encountered in significant concentrations in groundwater the various worldwide UCG trials.

Laboratory investigations carried out prior to the RM1 test drew the following conclusions in relation to the mechanisms and causes of contaminant production (Glaser *et al*, 1986 and 1987):

- pyrolysis liquids and gases are a far more important source of potential groundwater contaminants from UCG than thermally altered coal. The flow of these liquids and gases outward from the gasification cavity at any time during and after UCG operations can result in significant groundwater contamination if the process is not adequately controlled;
- water flow through the coal and into the cavity will limit postburn coal pyrolysis;
- cooling of the mass of rubble in the postburn cavity can limit postburn pyrolysis; and
- the size of the steam zone resulting from the gasification process is a key factor affecting postburn coal pyrolysis. Wide steam zones result in significantly more postburn coal pyrolysis than narrow steam zones.

In general there was little evidence of significant leaching potential from inorganic contaminants in the rubble/ash left after gasification, with the possible exception of boron that was encountered at Rocky Mountain 1.

2.3.2 Groundwater Pollution Events and Transmission Mechanisms

Early USA Tests

The shallow depth of the Hoe Creek and Hanna trials dominated the hydrogeology, particularly as the cavities intersected all, or nearly all, of the overlying geological units. The history of the two separate series of tests (Hanna and Hoe Creek) has been discussed previously. At least three of the seven tests carried out in total resulted in groundwaters with concentrations of pyrolysis products and leachates that significantly exceeded preburn or Department of the Environment (DOE) target restoration concentrations. Various environmental analyses were carried out, however subsequent reviews of sampling procedures have cast doubt on the validity of some of the higher concentration readings recorded (Covell, 1986), so some caution needs to be exercised when quoting recorded values.

Hanna I produced large, asymmetrical cavity containing approximately 300,000 gallons of water. Hanna III was smaller test resulting in 170,000 gallon cavity. Phenol concentrations exceeding DOE target concentration values for phenols were encountered within the Hanna I cavity water, however there is some doubt over the readings as site restoration activities showed hardly any phenols (Oliver, 1987). Concentrations of 7,000 mg/l TDS and 4,900 mg/l sulphates were found within the Hanna III reactor waters following groundwater recharge after gasification (Oliver, 1987). Some limited migration was found to be occurring within the coal seam, but not in the overlying units. TDS and sulphates were successfully improved by flushing with better quality water from the Hanna I cavity.

Condensate from the processes gases in the Hanna IV test contained very high phenolic concentrations, at nearly 7,000 ppm (Humenick *et al*, 1981).

During the Hoe Creek tests, contaminants associated with, on average, roughly 10% gas losses, were carried beyond the reactor by elevated pressures. These tests also indicated that other contaminants were transported by the gas escapes, with estimates of up to 200 ft laterally for the Hoe Creek tests (Stephens, 1981).

Phenol concentrations of up to 10 mg/l were encountered 10 m away from the smaller Hoe Creek II reactor, but these reduced to less than 1 ppm after two years. Initial cresol concentrations were higher (22 ppm), but showed a similar pattern of reduction (Wang and Mead, date unknown). Phenol concentrations in the coal seam near Hoe Creek III (40 m away) peaked at around 4 ppm just after the test, but reduced to around 1 ppm within three years (Wang and Mead, date unknown).

In terms of long term concerns, benzenes were considered by the United States Environmental Protection Agency (USEPA) to be of most concern due to their potential persistence. Although pump and treat remediation was carried out using activated carbon for removal of organic compounds that improved groundwater quality, some contaminants, especially benzene persisted in and around the coal seam. Benzene in one seam remained in concentrations up to 1 ppm and benzene and phenols were also detected in the channel sand aquifer (which was intersected by the burn cavities) (USEPA, 1999).

The Rawlins UCG series were shallow trials on a steeply dipping coal seam, but detailed geological information was not available. Contamination by phenol and benzene contamination was recorded, occurring above Maximum Allowable Concentration (MAC) levels mainly within the coal seam itself. The distribution of contaminants was not uniform and benzene was detected up to 600 ft away. Concentrations in the coal seam generally ranged between 0.005 and 0.001 mg/l (although one elevated reading of 49 mg/l was encountered around 600 ft away). Concentrations in the overlying sandstone aquifer were less, between 0.0068 and 0.015 mg/l, but reached 20 mg/l shortly after the end of the test in one well near the reactor. The contamination concentrations decreased by a factor of 10 after 3 years (USEPA 1999).

Rocky Mountain 1 Test

Preparations for the RM1 test included general assessments of the potential for caving/roof collapse for various strata (Daly *et al*, 1987). They also raised the issue of changes to the physical characteristics of rocks caused by high temperatures that can influence their strength or caving characteristics. This has limited relevance to the UK due to the depth of the proposed trial, where it is expected that the strata above the reactor will almost certainly collapse irrespective of its strength.

As noted previously the RM1 test consisted of an ELW and a larger CRIP test. The top of the coal seam was between 350 and 365 ft below ground level. The overburden consisted of approximately 150 ft of claystone and siltstone with

interbedded sandstone immediately above the coal seam, then a primarily sandstone member around 75 ft thick. Above this were silts, shales and a thin coal seam to surface (Lindblom *et al*, 1993). This type of geology is similar to UK Coal Measures, although this was much nearer the surface than anticipated in a UK trial site, so there will be large differences in confining pressure and hence coal permeability. There was no apparent hydraulic continuity between the overburden aquifers and the coal seam prior to the test (Lindblom *et al*, 1993).

A cone of groundwater depression was maintained at all times around the ELW and CRIP cavities during the test. This meant that groundwater flowed towards the cavities throughout the duration of the test and during the monitoring phase.

Water quality tests within the RM1 cavity itself indicated significantly elevated concentrations of boron, ammonia, phenol and volatile organic aromatics (VOA) (up to 12 mg/l ammonia, 0.8 mg/l phenols, 60 mg/l total organic carbon (TOC) and 2,700 TDS) after the test before the start of the first pumping remediation carried out at the site.

During the tests, ammonia, boron, cyanide, phenol, TDS and TOC were monitored to identify possible gas excursions. Gas escape did occur during operations and water from wells to the south and west of the test area exhibited the greatest change in groundwater quality, which was contrary to the generalised flow of groundwater. This indicated that gas was flowing towards the areas of highest transmissivity (as indicated by the pumping tests), rather than according to groundwater flow.

Post operations studies concluded that these gas flows were generally up-dip, indicating that the gas was migrating along the top of the coal seam, constrained by the base of impermeable strata layers above (Beaver *et al*, 1989). The migration of gas only occurred during the startup phase when pressures were elevated above hydrostatic, however the result was rapid and widespread, resulting in changes to groundwater quality beyond the furthest monitoring point (120 m away). This appears to have been caused by the high transmissivity of the coal towards the south west (approximately 0.22 m²/day). This conclusion is supported by the fact that gas losses were higher from the CRIP reactor, which was nearer the area of high transmissivity, than the ELW reactor (Boysen *et al*, 1990).

Relatively short lived, but significant pH declines (in the coal seam water) were notably associated with gas escapes, indeed the number of gas escapes was strongly correlated with the drop in pH. The impact on soluble ions was not determined because these were not being monitored as part of the test. Trends of ammonia and sulphate also clearly indicated that these were associated with gas escapes. TOC also increased in well that experienced gas

escape, probably caused by acetic acid, acetone and traces of benzoic acid (Lindblom *et al*, 1993).

Long term (6+ years) monitoring of wells around the cavities showed a return to within baseline maximums, however this took some time and elevated concentrations of TDS, sulphates, and ammonia were experienced for a number of years after the test.

Phenol was only encountered outside the cavity in the immediate overburden between the two test cavities, and this only ranged up to 0.098 mg/l. Benzene was encountered at low concentrations in a few places in the coal seam outside the reactor, the maximum concentration was only 0.044 mg/l; again this was encountered between the two reactors.

It is important to note that CO₂ and sulphide concentrations increased in the postburn product gas. It was thought that this may have been indirectly related to solubilisation of these gases in surrounding groundwater as gases escaped during the test. These gases in solution were subsequently released from groundwater as it flowed into the postburn UCG cavities and was converted into steam. This would account for the low sulphur content encountered in the gases that escaped during operations and could account for the lowering of groundwater pH (which could be associated with dissolved sulphur and CO₂). The released steam contained considerable amounts of phenols, sulphide and ammonia (Boysen *et al*, 1990)

El Tremedal

The target seam at El Tremedal was located at between 500–700 m below ground level (bgl), in the Jurassic Lias strata, just beneath a Cretaceous discontinuity. Hydrogeologically the natural flow regime was from the coal seam to the immediate sandstone overburden (Green, 1999). The coal permeability was fairly average for a coal (1.96 mD), but does not indicate a high degree of continuous cleats/fractures. The sandstone permeability was fairly average, at around 1.7×10^{-7} m/s. The Lias aquifer below the coal seam was effectively isolated by a layer of impermeable limestone and in any case the natural upward flow gradient would prevent downward migration of contaminants (Green, 2003).

It was thought that groundwater flow into the cavity would be limited as clays above the immediate sandstone overburden would prevent inflow from the higher permeability Albian sandstones. However, this proved not to be the case as high levels of groundwater inflows were experienced during the test that caused operational difficulties. Although information is limited, it appears that either natural pathways or pathways opened up by the caving of the reactor caused hydraulic connection with the higher permeability sands through some 40 m of clays. As water flowed into the cavity and was removed to surface with product gases, a drawdown would have occurred that would increase the hydraulic gradient towards the reactor. It is likely that this is why

groundwater inflows became more and more of an issue as the test progressed (Mostade, 2003).

The fact that high volumes of water were flowing through the overburden and the coal seam into the reactor probably resulted in a smaller char zone that was 'self cleaning' as contaminants were pulled into the cavity with the incoming groundwater. As a result, no organic pollution was detected in strata around the gasification reactor during or immediately after the trial (Green, 2003). Reciprocal to this was the fact that contaminant levels in water separated from the product gases at the surface were very high.

It is interesting to note that contaminant levels in water contained within the product gas during gasification were very high, but the wastewater left in the cavity post gasification was relatively clean, especially in relation to pyrolysis products. The reasons for this are not entirely clear, however the following mechanisms may have been responsible:

- as water was flowing into the cavity, pyrolysis would not have continued for long after gasification ceased. Therefore the quantity of char produced post gasification would have been relatively limited;
- during gasification, the char zone was being 'dynamically' created. This means that the groundwater was effectively constantly flushing through a 'new' char zone, as opposed to post gasification where a static char zone was being flushed; and
- post gasification and towards the end of the burn, as new pathways opened up to the overlying aquifer due to caving, the majority of the groundwater is likely to have been entering via the overburden rubble, rather than the char zone in the coal.

This may have resulted in a situation whereby the groundwater being flushed into the cavity during operations was constantly being passed through a 'fresh' char zone, whereas post gasification the whole of the volume of water within the reactor passed through either the caved overburden or the static char zone. This could mean that a lower quantity of contaminants were contained within a much larger body of water post gasification, resulting in the lower concentrations encountered. It is not clear what proportion of the contaminants in the char zone were being flushed into the cavity during and after gasification.

There was some gas escape in this test during the linking phase (when the injection zone was being linked with the production well) that lead to small reductions in pH in the coal seam local to the gasification reactor. There was no interaction detected between waters around the reactor and groundwater contained in higher aquifer systems used for human consumption, probably due to the presence of significant layers of montmorillonitic clay and Lower Cenomanian marls above the target seam. It should be noted that the monitoring regime was very limited for this study and the natural upward flow

regime would have taken some time to be re-imposed, but due to the remoteness, depth and geology of the site, it is unlikely that human abstractions or the local river system will be affected.

Australia

Publicity literature from the study claims that (Blinderman and Jones, 2002), following a burn of more than 20,000 tonnes of coal for the Chinchilla project, no groundwater contamination, surface subsidence or surface contamination had been reported. The Australian Environmental Protection Agency (EPA) confirmed that all environmental objectives had been met. They also confirmed that the environmental monitoring and management system developed by Linc Energy for the trial was sufficient without independent monitoring from the EPA (Slater, 2003).

2.3.3 Groundwater Contaminant Attenuation, Mitigation and Remediation

Analysis of groundwater from the Tono 1 cavity two years after completion of the burn showed relatively low concentrations of the various constituents. The highest mineral concentrations were sulphate (185 mg/l), calcium (23 mg/l) potassium, magnesium and iron. This appears to be due to natural attenuation, although the 'fate' of the contaminants is not known.

One of the main objectives of the RM1 test was to look at the effectiveness of the 'clean cavern' concept that had been developed based on previous trials. The 'clean cavern' concept was developed to limit the groundwater impact of UCG and was based on the following principles (Boysen *et al*, 1988 and 1990):

- gas losses to the surrounding underground strata must be minimised during and after gasification;
- the flow of pyrolysis products from the UCG cavity to the surface through the process wells must be sustained after gasification is terminated; and
- postburn cavity temperatures must be reduced as quickly as possible to minimise the production and release of pyrolysis products.

It is important to note that experiments into limiting postburn pyrolysis indicated that flushing with water immediately after gasification was not beneficial and was potentially damaging due to the increased cavity pressures caused by steam created by the water injection (Boysen *et al*, 1990). In line with the 'clean cavern' concept, the objectives of the venting, flushing and cooling of the two UCG cavities were:

- to minimise postburn contaminant generation from pyrolysis products by accelerating the cooling of the cavities and preventing pressure build up post gasification;
- to maximise the removal of potential organic and inorganic groundwater contaminants from the underground strata by pumping and treating contaminants; and

- to maintain the flow of groundwater towards the cavities by pumping water from the cavities and hence maintaining a hydrostatic gradient towards the cavity areas.

This was partly successful, but the venting was hampered by the fact that water tended to accumulate in the lower parts of the rubble filled cavity, whilst steam was still being generated and accumulated in the upper parts of the cavity. The wells were no longer able to vent gases once water levels reached their bases, so pressure built up in the top of the reactor. This feature may have been encountered in the Spanish trial, as discussed later.

The RM1 site was subjected to two cavity pumping operations that influenced the hydrogeological regime post gasification. The first was carried out shortly after the end of the test and the second was carried out a year later, after groundwater had collected within the cavity. Results and treatment methods are discussed later. All of the detected contaminants, with the exception of boron, were successfully reduced to around baseline levels after the first restoration pumping. Contaminant loads in groundwater during remediation were generally lower than anticipated, but this was thought to be largely due to the contaminant removal provided by the venting operations described above.

Cavity pumping was carried out at El Tremedal, but concentrations were low during the first pumping and there were virtually no elevated concentrations detected during the second test pump. The quantity of phenols produced during the first cavity wash was less than 1 kg (based on concentration readings and estimates of the volumes treated), which would appear to be a small portion of the potential phenols produced by postburn pyrolysis. Therefore it may be that phenols were only flushed from a few 'preferential flow paths' in the char zone by the groundwater post operation and most of the contaminants remained entrained within the coal. Longer term monitoring results would be required to determine whether all of the contaminants had been effectively removed or dispersed by the time of the second cavity wash, or whether there is a longer term leaching potential from the pyrolysis zone. Summary reports for the Chinchilla trial indicated that operations were always carried out to ensure that gasification pressure in the gasifier was always 'slightly less' than the hydrostatic pressure of fluid in the coal seam and surrounding strata. This prevents product loss as well as contamination. Monitoring of hydrostatic pressure in key boreholes during the process was therefore a key element. Reports from the trial also indicated that heat loss from the reactor was 'minimal' due to the creation of an effective 'steam jacket' due to groundwater ingress (Walker *et al*, 2001).

2.4 PAST EXPERIENCE OF WASTEWATER TREATMENT AND REMEDIATION

2.4.1 Origins of Wastewater

Past experience has shown that four distinct phases exist in the life of a UCG project. Each phase has the capacity to generate wastewater and each phase may also present a range of disposal options.

Mining to Open the Facility

The initial mining operation is likely to generate wastewater which is contaminated with solids from the geological strata. The wastewater generated in UGC development will be no different than that expected from conventional operations. Consequently best practice from mining operations should be observed.

Generation during the Operation of the Site

Aromatics are not produced by an efficient gasification process, so during continuous and efficient gasification they do not appear in the product gas stream. However, if excessive infiltration of groundwaters occurs then wastewaters will be generated that may have to be treated during operations. This situation occurred in the Spanish trial and resulted in operational difficulties and additional operational costs.

Operational treatment and use of water is discussed in Section 5. Ideally, any water produced during the operation of the reactor will be re-injected as product water. This may require some form of treatment, as discussed in Section 5 however there is no experience of this from previous trials.

Generation during Flushing and Venting:

After gasification, steam is injected to evacuate residual gasification and pyrolysis products. The volume of the cavity water to be treated depends on volumes of the cavities and the rate of influx.

Generation during Cavity Flushing/Remediation:

After gasification, the waters within the cavity may be pumped to the surface to remove them from the sub-surface environment and maintain groundwater flow towards the cavity. This has been done in a number of previous trials

2.4.2 Past Experience of Wastewater Treatment

Experiment Site: RM1 UCG Cavities, Hanna, Wyoming

Two pump and treatment operation phases were carried out at the RM1 site to remediate cavity waters post gasification. Prior to flushing, steam was injected into the cavity to evacuate residual gasification and pyrolysis products, strip potential groundwater contaminants from the cavity, and cool the cavity to cease post gasification pyrolysis.

The gasification cavities remained vented to the surface to promote influx of water into the cavities after the venting, flushing, and cooling operations were

completed. The direction of the ground water flow was inward toward the cavities, flushing any groundwater contaminants from adjacent areas back into the cavities. During treatment, the pumped water was treated to remove colloidal and dissolved organics, heavy metals, and ammonia.

The constituents of the wastewater pumped from the cavity during the two operations are shown in Tables 2.5 and 2.6.

Constituent	Concentration (ppm)
Phenol	0.074~0.650
TOC	23~46
Ammonia	6.9~10.6
TDS	2140~2710
Boron	0.664~1.52
Sodium	765~840
Chloride	26~51
Sulphate	880~1130

Table 2.5 - Constituents of Wastewater Pumped during First Cavity Treatment (Composite Samples for Aug and Sep 1988)

Constituent	Concentration (ppm)
Benzene	<0.005
Chloroform	<0.005
Bromodichloromethane	<0.005
Phenol	<0.020~0.040
Ammonia	7.9~11.0
TOC	17~22
TDS	2280~2890
Boron	0.64~1.30

Table 2.6 - Constituents of Wastewater Pumped during Second Cavity Treatment (31 July to 15 Aug 1989)

The treatment target was to facilitate the discharge of the resulting clean water to soil surface as a mist. The target restoration values (TRV) were: phenol < 0.020 mg/l, ammonia 3.2 mg/l, boron 0.007 mg/l, TOC 27mg/l. Spraying on to land would be less favoured in the UK due to the land take requirement and potential risks to surface and groundwater.

Summary notes on the methods of the first experiment (flow rate 100 gpm) are as follows:

- gravitation separation and air flotation: 10,000 gal (37,850 l) tank;
- flocculation: 1,630 gal (6,170 l) chamber, including 50% aqueous chlorine or 12% chlorox™ solution to oxidize cyanide and ammonia

and 50% sodium hydroxide solution to raise pH and react with heavy metals;

- tuber settlement, precipitants included: metal hydroxides, residual cyanates, calcium carbonates and ash. The slurry was sent to be incinerated;
- two stage pressure filter to remove suspended solids;
- neutralisation using 93~98% sulphuric acid;
- pumping through a series of two carbon absorber units: 1.5m in diameter and 2.4m high, contain 2.8m³ of activated carbon; and
- two holding tanks followed by discharge through atomizing nozzles.

Summary notes on the effectiveness of the first experiment are as follows:

- ammonia was effectively reduced by chlorine oxidation (91~95% reduction), but ammonia only slightly elevated above the baseline concentrations in any case;
- carbon adsorption effectively removed phenols from the groundwater but was less effective in reducing TOC;
- the groundwater did not contain measurable concentrations of heavy metals. Adding sodium hydroxide had little impact other than raising the sodium concentration of the treated water;
- boron was not significantly reduced even if it was the only inorganic significantly above the baseline concentration. However, the concentration was too low to be considered as an environmental problem;
- the addition of chlorine, sulphuric acid, and sodium hydroxide increased the TDS concentration of the treated water that was deposited on the soil; and
- the process was only sufficient due to the carbon adsorption and spray evaporation used in the treatment.

In the second experiment (flow rate 100 gpm), the surge tank was then pumped to the anthracite and silica sand filter. Two carbon towers were used, as described above. Effluent was stored in a surge tank prior to the atomizing spray system.

The treatment system for the second experiment was not effective in removing targeted constituents:

- groundwater quality in the cavity wells was near baseline quality. Boron was the only constituent that was significantly elevated above baseline concentrations;
- the carbon adsorbers had little or no impact on removing phenols and TOC. The possible reasons for this were capability reduction by the addition of chlorine and contamination in the adsorber units. This meant

that chloroform and bromodichloromethane were introduced from the carbon adsorber units; and

- although benzene was detected in the cavity wells during quarterly sampling, it appears to be associated with isolated pockets of a source material, probably tars. Because benzene has low solubility in water, the leaching media (water) has to be relatively stagnant to accumulate detectable amounts. When the leaching media is not stagnant the benzene leach rate is so slow that it is diluted below detection limits.

2.4.3 Spanish Study

For the El Tremedal trial, excess water produced during gasification was noted as a major problem both technically and economically. The ingress of water was much higher than would be considered ideal; consequently a stream of wastewater was generated throughout the trial. Pollutants, as indicated by the monitored phenol, peaked towards the end of the trial and reached over 500ppm. This was categorised as 'foul water', which had the contaminant attributes shown in Table 2.7.

Contaminant	Recorded Concentrations
Phenols (ppm)	2.6 – 575
Ammonia (ppm)	5.9 – 1080
Sulphurs (ppm)	0.94 – 148
Conductivity ($\mu\text{S}/\text{cm}$)	1410 – 5640
COD (ppm)	102 – 5880
pH	8.4 – 7.6

Table 2.7 - Contaminant Attributes for the Wastewater for the El Tremedal Trial

The foul water was tankered off site and disposed of at a registered site. These costs were considered high and the option to create a treatment plant for the cavity wash water was investigated.

A selection process for the appropriate treatment options was performed. The anticipated wash water quality was analogous to the end of trials wastewater with the inherent high phenols. The selected process was hydrogen peroxide (H_2O_2) oxidation, which was perceived to have the following benefits:

- the H_2O_2 , unlike chlorine does not have the associated risks of halogenated oxidation products;
- it was considered versatile in its ability to treat pollutants such as iron and sulphides or difficult to oxidise (solvents gasoline and pesticides);
- totally miscibility with water; and

- level of control: adjusting dose, pH, temperature, reaction time and /or catalyst) H₂O₂ can be optimised for the type and concentration of pollutants.

The potential disadvantages of the adopted process included the use of corrosive and hazardous chemicals and the generation of precipitated solids. The protocol adopted for the treatment entailed:

- batch processing;
- pH adjustment using sulphuric acid;
- ferric chloride and of hydrogen peroxide dosing followed by caustic soda neutralisation (after 5.5 hours);
- flocculent addition (aluminium polychloride); and
- solid settlement followed by sampling & disposal of wastewaters

Although this process was designed to treat the high concentration of phenols. The actual concentrations in the cavity wash water < 0.05 to 2 ppm. Possible reasons for this have been discussed previously. This level of pollutant is much lower than the 500 ppm previously noted. As a consequence the treatment capacity was in excess of that required.

3. ASSESSMENT OF TECHNICAL FACTORS INFLUENCING THE IMPACT OF UCG ON GROUNDWATER QUALITY

3.1 CHEMICAL AND PHYSICAL PROCESSES INVOLVED IN CONTAMINANT FORMATION

3.1.1 Chemical and Physical Processes during Gasification

In plan view, most of a developed reactor will be filled with caved and compacted roof strata. The interstices between the caved fragments will be filled with a mixture of oxygen and (probably wet) steam. The temperatures in this region will not generally exceed the saturation temperature of the steam at the reactor pressure (250-300°C). The ash will form a layer on the reactor floor, and will generally be infused with injected/groundwater. Gas flow velocities in this region (from the injection point to the coalface) will be low, ~ 1-10m/hour, corresponding Reynolds numbers will be in the range 1-1000. The gas flow will be laminar and there will be no significant mixing in this region. The corresponding pressure gradients will be low; the pressure drop through the developed reactor will be <<1bar and negligible relative to the pressure drops within the production and injection wells.

As the input gases approach the coal/char face, they will enter the reaction zone, which will be filled with product gas at a relatively high temperature, 700-900°C; here the oxygen will combust the product gas (it is most unlikely that an input oxygen molecule ever survives to reach the coal face). This process is highly exothermic and the local temperature will rise and the gas will convect upwards. There will be a corresponding downward convection

immediately adjacent to the coal face, where the partially oxidised product gas reacts endothermically with the coal/char. The intensity of this convective circulation is proportional to the temperature gradient within the reaction zone and the square of the reactor pressure, and at pressures of 50-100 bar the basic physics dictates that mixing in this zone must be rapid and continuous.

High pressure oxygen and steam are potent scavenging agents for any form of hydrocarbon; it is most unlikely that unreacted char, carbonaceous mudstone, high molecular weight volatiles etc survive the outward transit of the reaction zone; the central regions of a developed gasifier (comprising most of the total volume) are therefore chemically inert, with the exception of the ash layer, which may contain water soluble metallic salts.

The thermal conductivity of coal is low and in itself unlikely to create a pyrolysis zone of any depth or volume. Penetration by hot product gas is likely to be a far more effective heat transfer mechanism, with the steam component being the most efficient agent. At elevated pressures the condensation temperature of steam is typically $\sim 300^{\circ}\text{C}$, and the latent heat is still uniquely high. Even though 300°C represents the lower temperature boundary of coal pyrolysis (which occurs in the interval $300\text{-}1000^{\circ}\text{C}$) high pressure process steam clearly makes a significant and perhaps the major contribution to pyrolysis. However, since coal always contains intrinsic water, the water to steam phase change in the intrinsic water will itself absorb considerable process heat and limit the extent of the pyrolysis zone (this may be the 'steam jacket' effect referred to in previous trials).

Figure 3.1 shows schematically the different regions present in the side wall of the gasifier. The cavity wall represents the general position where the coherent char structure breaks down into char/ash rubble, and the drying front is the location where the vapour pressure of the water in the coal (moisture plus water influx) reaches the cavity pressure. In the layers of coherent char and dry coal, the heat and mass fluxes are nearly normal to the cavity wall and involve mainly heat conduction. Pyrolysis, the centre of production of potential organic contaminants (tars, oils, phenols, etc), takes place in the dry coal layer.

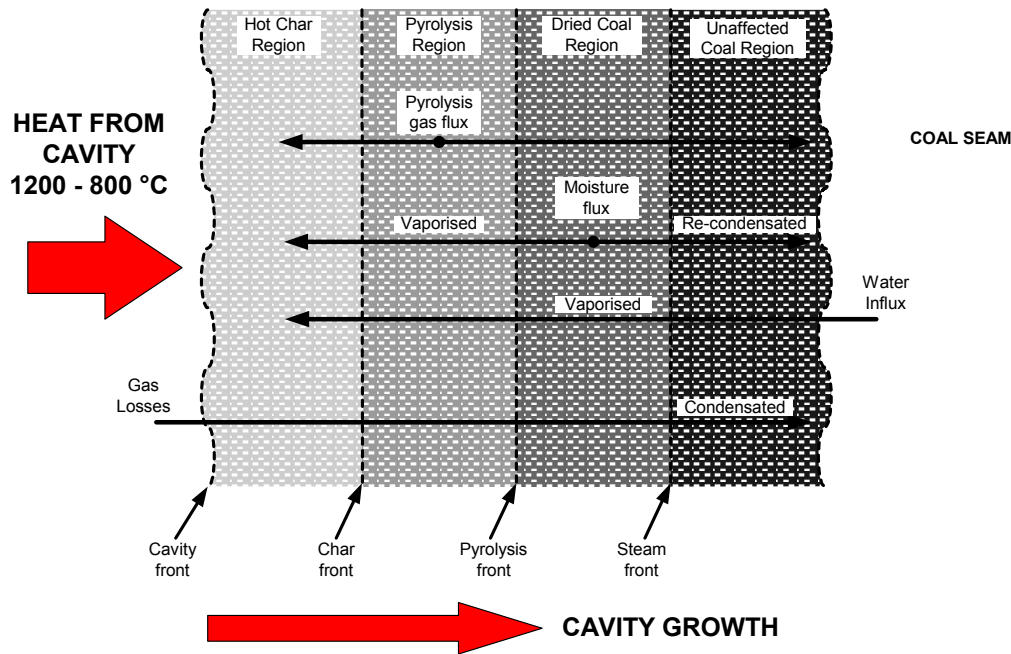


Figure 3.1 - UCG Cavity Side Wall (courtesy of WS Atkins)

Previous trials have shown that increasing the in-situ reactor pressure is operationally beneficial in all respects, but since gas losses from the reactor are probably permanent and inevitably constitute a source of contamination, they must be minimised, and if possible prevented altogether. In a competent, dry formation the theoretical limit on gas escape is the formation fracture pressure (typically twice the hydrostatic pressure). However, in the present state of understanding and in the absence of site specific information, prudence dictates that the reactor pressure should be limited to the hydrostatic. For an inclined seam/reactor, this should be the hydrostatic pressure corresponding to the highest point. If significant groundwater is anticipated, steeply dipping locations should be avoided.

However, elevated pressures also mean that gasifying with pure oxygen and steam are operationally advantageous (the 'break even' range is around 10-20 bar). There are also significant environmental disadvantages of using air instead of oxygen, as the nitrogen within air increases the production of ammonia compounds and promotes the synthesis of hydrogen cyanide.

Therefore there is an environmental balance relating to pressure: increasing pressure is beneficial in terms of reduced contaminant production, but it increases the probability of gas escape. This is one of the reasons why depth is so important as it allows pressures in the reactor to be increased without exceeding in-situ hydrostatic pressure.

3.1.2 Chemical and Physical Processes During and After Shutdown

At the conclusion of gasification, there will be a zone of devolatilised coal around the periphery of the reactor, as seen in plan. Organic contaminants

(cyclic and polycyclic hydrocarbons etc) that are decomposed in the reaction zone whilst gasification continues, are formed and then retained within this zone post gasification. This is because when oxygen ceases to reach the coalface, temperatures will still be adequate to produce organic contaminants, but there will be no in-situ decomposition.

The strategy at shutdown is therefore to cool the reactor as quickly as possible to minimise the post gasification formation of organic pollutants, as follows:

- oxygen injection is terminated;
- water injection is maintained, unless shutdown has been compelled by excessive groundwater ingress;
- the choke valves on the production wellhead are opened towards their maximum, to vent the reactor as quickly as possible and to maintain gas lift (of water) conditions within the production well; and
- since an in-situ reactor is also a gas storage system, and most of the gas stored will be input oxygen and steam that has not yet reached/reacted with the coal, gas production will continue during depressurisation; the gas quality will decline, and in the later stages it will contain elevated proportions of CO₂, steam (and ultimately liquid water) and organic pollutants. Depressurisation might typically take approximately one week for a successful experimental reactor; and probably considerably longer for a commercial system.

When an UCG operation is shut down, a large volume of hot rubble is contained within the gasifier. The rubble is heated to temperatures in excess of 800°C and the sensible heat is sufficient to continue to heat the overburden and coal that surround the gasifier for a quite long time. Heat is conducted away from the rubble region into the coal, continuing to expand the char and dry coal regions, and generating additional steam and pyrolysis products.

If the reactor is not vented after shut down, the cavity pressure may rapidly equal or exceed hydrostatic pressure allowing large quantities of pyrolysis products to be produced and transported away from the cavity in the surrounding coal and strata. On the other hand, maintenance of a pressure less than hydrostatic pressure by cavity venting will allow water influx to cross/cool the reactor side wall and consequently limit the production of postburn pyrolysis products.

For a suitably vented reactor with any significant development it is considered most unlikely that there exists within the char zone sufficient residual thermal energy to fill the reactor with steam at a pressure exceeding hydrostatic, since the specific heat of char is modest, ~ 0.3 cal/gm and the enthalpy of high pressure steam is uniquely high, typically ~ 600cal/gm.

During venting, groundwater influx will increase as the difference between hydrostatic pressure and the reactor pressure increases. The impact that this

increased groundwater influx will depend on the rate of inflow that will occur. If flows are reasonably high, then this can have the effect of 'quenching' the reactor (thus preventing the continued pyrolysis of coal in the reactor walls) and 'flushing' pyrolysis products from the reactor walls into the cavity. In locations where groundwater flow is not likely to be high enough to cool the cavity quickly enough to limit pyrolysis, water may be injected from the surface.

At the conclusion of venting, the reactor will be filled with liquid water. The system will then cool to the in-situ geothermal temperature. There will then be the option of circulating the system to flush residual contaminants within the reactor and production system. Liquid phase oxidation in-situ using H₂O₂ or possibly ozone is also an option.

After the venting, flushing and cooling operations are completed, the gasification cavities will remain full of water with dilute concentrations of pyrolysis products and leachates that will still exceed preburn concentrations. Contaminants normally associated with these waters will include phenols, TOC, sulphides, sulphates, dissolved solids, ammonia, boron and metals.

After these operations, contaminant transport will be toward the cavities as long as the pressure gradient is still maintained in this direction. As the cavities fill, however, the natural flow gradient will progressively be re-established and groundwater may transport contaminants out of the UCG cavities. In previous trials, natural restoration processes have been shown to restore cavity water quality to near baseline conditions after a while. However, at the depths proposed in the UK, biological degradation (which is normally the most rapid form of restoration) is likely to be very low or absent, so slower physical (dispersion and adsorption) and chemical activity may be required to restore the groundwater.

3.1.3 Nature of the Contaminants

The physical processes discussed previously mean that the operation and shutdown of a gasification reactor can result in the following emissions that may cause contamination of groundwater in and around the reactor:

- escape of the product gas;
- escape of gases that build up after operations have ceased;
- leaching of pyrolysis products produced by incidental pyrolysis of the reactor walls (during and after gasification); and
- leaching of inorganic contaminants from the mineral ash produced by the gasification process (within the reactor and pyrolysis zone).

The in-situ groundwater at depth can also present a contamination hazard to higher aquifers due to high levels of mineralisation.

Product Gas and Post Operational Gases

At high pressures and temperatures the relevant gas solid chemical interactions occur rapidly and establish a product gas composition approaching that of thermochemical equilibrium, in which the concentrations of higher hydrocarbons (ethane and above) is small and the concentration of cyclic/polycyclic pollutants is negligible. The main components of the product gas that pose a risk to groundwater are:

- sulphides and chlorides; and
- ammonia and derivatives (hydrogen cyanide).

There is also a theoretical possibility of volatile electronegative metals (arsenic, mercury, lead, etc) present essentially in the ash, being reduced and entrained in the product gas in vapour form or as finely divided liquid droplets. If present the concentrations are likely to be extremely small and are frankly speculative. An approximation of the likely make-up of the product gas is provided in Table 3.1.

However, it should be noted that during gas 'escapes', product gases will effectively be 'pushed' through the pyrolysis zone and water saturated coal or strata beyond. They will cool during transition and will obtain characteristics more similar to the shutdown and venting phases discussed below.

During shutdown and venting, the proportion of high molecular weight organics in the product gas will increase, and water solubility will become an issue as temperatures fall and steam condenses. Hydrogen chloride, ammonia, hydrogen cyanide etc will then all be in aqueous solution and the process strategy may be to gas lift the polluted water for subsequent surface clean up.

Parameter	Molar Composition of Raw Product Gas (mol %)	Molar Composition of Dewatered Product Gas (mol %)	Approximate quantity produced at gas production rate of 400 tonnes/day (tonnes/day)
H ₂ O	35.0	-	120
CO ₂	24.5	37.7	180
CO	10.0	15.4	47
H ₂	15.0	23.0	5
CH ₄	12.5	19.2	33
H ₂ S	0.8(1)	1.2	4
HCl	0.2(2)	0.3	1
NH ₃	0.4	0.6	1.1
N ₂	0.9	1.4	4.2
C ₂ H ₆	0.4	0.6	1.9
C ₃ H ₈	0.2	0.3	1.4
C ₄ + (tars, phenolics, etc)	0.1	-	Trace

(1) – based on approximate coal sulphur content 1.6%

(2) – based on approximate coal chlorine content of 0.4%

Table 3.1 - Likely Product Gas Make-up

Based on the findings of above ground coal gasification, other pollutants that may be present in the produced gas in gas escapes and post gasification, in minor to trace quantities, include the following:

- particulate matter;
- hydrogen cyanide;
- carbonyl sulphide;
- other PAHs;
- methyl mercaptan;
- heavy metals, and;
- dioxins and furans.

The values in Table 3.1 could theoretically be used as an approximate guide to determine the volume of ammonia, sulphides and organic compounds contained in a gas escape. However, this type of mass balance is practically of very limited use due to the complex interaction of the contaminants with groundwater, as discussed later.

Leachates and other Dissolved Contaminants

The difference between 'leachates' and other aqueous phase contaminants is really only an issue of terminology. 'Leachates' are formed when groundwater passes through a solid or liquid and it leaches substances from that solid or

liquid. Other contaminants can dissolved in groundwater when it is either present in the reactor or when a proportion of gas escaping from the reactor is dissolved in groundwater as it passes through saturated strata. In either case a potentially mobile, aqueous phase contaminant is produced.

A summary of the potential contaminants that may be leached from the reactor and their point of origin, is presented within Table 3.2.

Gasifier Zone	Potential Contaminants		
	PAH/Phenolics	Heavy Metals	Heavy Metals (reduced)
Pyrolysis Zone	✓	✓	✓
Char	×	×	✓
Ash	×	×	✓
Rubble	×	×	×
Outflow Channel	✓(?)	✓	✓

Table 3.2 - Potential Contaminants that may be Leached from the Reactor

The pyrolysis process that occurs incidentally within the walls of the reactor (the char zone) results in the formation of coal tars and oils that become entrained within fractures in the coal seam (called 'cleats'). Various substances may leach from these products, but previous trials have shown that the lower molecular weight compounds such as phenols, benzenes and cresols are the primary contaminants. Leachate concentrations within groundwater depend upon the balance between leaching and adsorption within the coal around the gasification reactor. Studies carried out for previous trials have shown that the low molecular weight phenolic compounds are the least likely to be adsorbed by coal and high molecular weight PAHs exhibit the highest adsorption capacity.

The mineral matrix within the coal forms a layer of ash on the floor of the reactor, which can act as a source of a variety of inorganic compounds, including heavy metals. As well as product gas, the gasification of the coal produces a partially clinkered (occasionally vitrified) ash, which collects on the floor of the reactor as the process proceeds. The ash remains within the reactor.

The overburden above the coal seam is thermally altered by the process as it caves in and this may also provide a source of inorganic compounds. The emission of water bearing these compounds from the reactor can raise the TDS and sulphate concentrations, as well as other trace elements such as boron in the surrounding groundwater. However, these emissions are minor compared to gas escape and pyrolysis products and are not considered to have produced significantly elevated levels of contaminants in previous trials.

As discussed previously, there is an important interface between gas and leachates, as leachate products can be taken beyond the confines of the reactor and pyrolysis zone during gas escapes. Mechanisms for this are discussed in later sections of the report.

Poor Quality Groundwaters

It should be noted that the pre-existing groundwaters that are present in and around the coal seam may be of very poor quality, with high TDS and high concentrations of certain ions associated with the leaching of minerals over long periods of time. These groundwaters can represent a risk if the changes to underground strata and hydrogeology caused by the UCG operations causes them to flow to 'economically or environmentally significant' aquifers in the overburden. This is known as 'cross-contamination' of aquifer horizons.

3.2 FACTORS INFLUENCING MOVEMENT FROM THE UCG REACTOR

The quantity and nature of contaminants that escape from the reactor and surrounding pyrolysis zone are mainly constrained by operational factors, but also depend quite heavily on the availability of groundwater in the strata local to the reactor.

3.2.1 Factors Influencing Contaminant Escape during Operations

The various operational and structural impacts that influence this contaminant escape during gasification are summarised in Figure 3.4.

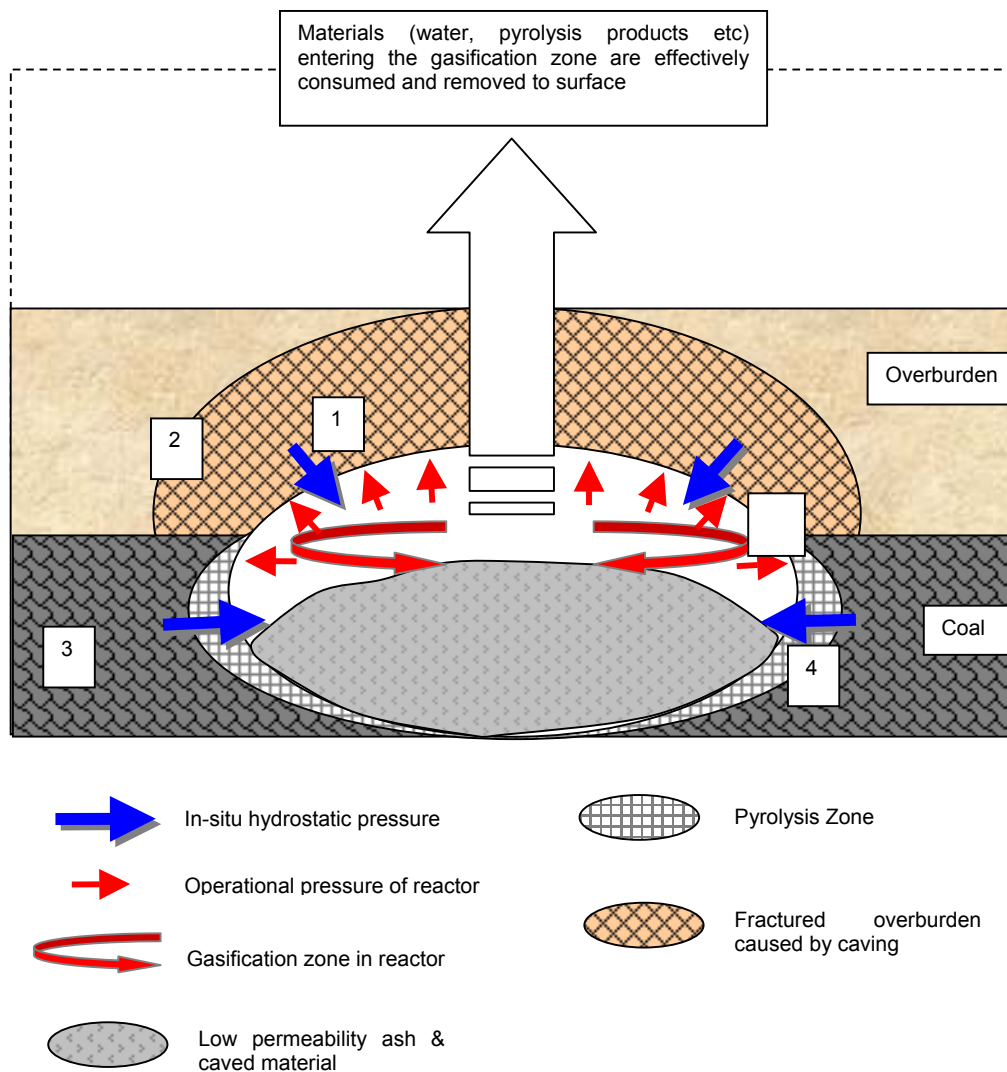


Figure 3.2 - Factors Influencing Contaminant Escape during Operations (courtesy of WS Atkins)

Notes on the factors (as shown in the diagram) are discussed below.

1. The primary boundary condition is thought to be the difference between the operating pressure and the hydrostatic pressure. Gases and pyrolysis contaminants in and around the gasification cavity should be 'contained' by groundwater if pressures within the gasification reactor are less than or equal to hydrostatic pressure (as groundwater flow will be towards the gasification reactor). Conceptually, the gasification reactor may be regarded as a perforated vessel, so if it is surrounded by water at a greater hydrostatic head than the gases inside the 'vessel', then water will flow into the chamber rather than gases flowing out.
2. If hydrostatic pressure is greater than reactor pressure, then the rock mass properties (strength, stiffness, permeability, storativity etc) of the overburden will dictate the amount of water flowing into the cavity from

the fractured zone created by the caving of the reactor, along with the pressure differential (the 'driving head').

3. Similarly, the properties of the coal around the reactor will affect the amount of water flowing into the cavity.
4. The difference in pressures and the nature of the coal will also affect the extent of the pyrolysis zone that is created during operations. The extent of the pyrolysis zone during gasification has been discussed previously, but it is likely to be smaller if operating pressure is lower than hydrostatic pressure and there is a good rate of flow of groundwater from the coal into the reactor.

As noted previously, losses of product gas to surrounding strata can therefore be prevented or controlled by exploiting coal seams in locations where the adjoining strata are relatively impermeable and by controlling the pressure within the reactor.

Although gas escape is unlikely to happen if the pressure gradient is towards the gasification reactor, exceptions may occur if there are any large, open faults or fissures around the gasification reactor that could cause localised dynamic reductions in hydrostatic head. Such incidents will be virtually impossible to predict or control and the emission of significant gas escapes over long distances is not likely by this method, however it does mean that some gas escape may occur even if sub-hydrostatic conditions are maintained.

As operational pressures in the cavity are reasonably controllable, the available evidence indicates that the main form of contaminant escape during the process is likely to be associated with short term gaseous emissions (a few days or less). Emission of aqueous phase contaminants not entrained within gas escapes beyond the immediate vicinity of the reactor is very unlikely during operations. This is because:

- groundwater is consumed as part of the process, so a 'cone of depression' is likely to form around the reactor, meaning that aqueous phase materials will flow towards the reactor; and
- if reactor pressure increases enough to create a head gradient that actually promotes groundwater flow away from the reactor, then permeability constraints mean that aqueous phase contaminants are unlikely to migrate more than a few metres from the reactor unless high pressures are maintained for a long time.

As a large reduction in hydrostatic head may occur as the gasification process progresses, operating pressures may have to be reduced as gasification progresses if pressures are to be maintained below hydrostatic conditions.

Studies into gas migration have shown that some differential in pressure between the reactor and the surrounding strata is required before gas will escape (Rodwell *et al*, 2000a), but that this pressure differential does not have to be large (in most studies it is around 0.1 MPa, or 1 bar). Further information on gas transport modelling is provided later in this section.

3.2.2 Factors Influencing Contaminant Escape post Operations

The various operational and structural impacts that influence the quantity and nature of the contaminants escaping the reactor and pyrolysis zone post operations are more complex. The basic premise remains the same, ie contaminants will tend to be contained if gas pressure in the reactor is maintained below hydrostatic pressure and groundwater flow is maintained towards the reactor.

During the post operation phase, the dispersal of heat and potential build up of gas pressures caused by inflowing waters turning into steam are important considerations. If the reactor is not vented, then gas pressure can increase as groundwater is turned into steam, which can lead to cavity pressures that are greater than in-situ hydrostatic pressure. If this happens then it will increase the size of the pyrolysis zone and 'push' gaseous and aqueous phase contaminants beyond the reactor zone.

If a reactor is fully vented, then the gas pressure so induced within the reactor cannot exceed the hydrostatic pressure between the base of the production well and the surface. However, if the reactor is large and has a significant inclination, this gas pressure may exceed the local hydrostatic pressure in the elevated region of the reactor away from the product well, so gas may be lost to the overburden in consequence. For a hypothetical reactor ~ 300 m long, each degree of inclination (to the horizontal) represents a potential pressure differential of ~ 0.5 bar, which strongly suggests that excessive inclinations between injection and production wells should be avoided. However, it should be emphasised that the concept of hydrostatic balance within UCG precludes any excessive coal seam inclination in a reactor of any significant extent, since the reactor pressure is limited in principle to the hydrostatic pressure corresponding to the highest point within the reactor.

Previous trials have shown that groundwater can tend to pond at the base of the reactor whilst steam forms in the caved strata above the base of the reactor. Where the production well has been used to vent post process gases, rising water levels have effectively isolated the well from the gases in the cavity and prematurely stopped the venting process. This is a shallow seam issue and it is not clear whether this would present a risk at depth, as the pressures involved mean the boiling point of steam is some 300°C, so the formation of significant quantities of steam is unlikely. The only way to prevent this blockage is to exhaust the water accumulating at well bottom by

an air lift system (injection of nitrogen in the annulus of the production well and producing the gas/steam/water mixture through the production tubing).

Leachate movement post operations will simply depend on the direction of groundwater flow around the reactor and the permeability of strata in the de-stressed zone around the reactor.

Cavity pumping has been used in previous trials to 'improve' the quality of water in and around the reactor. There are, however, some uncertainties associated with cavity pumping and treatment. Repeated pumping of the reactor after gasification will certainly help to maintain a cone of depression towards the reactor, which should prevent migration of aqueous contaminants beyond the reactor zone. It will also lower contaminant concentrations within reactor waters. What is less certain is whether the mass of organic contaminants in the char is significantly reduced by pumping operations. Experience from groundwater remediation of hydrocarbon spills shows that each phase of pumping simply flushes fissures in the rock mass, but the contaminants within the rock matrix remain and re-introduce contaminants to the fissures via the slow process of diffusion. If this occurs during cavity flushing then the remediation will only be short term and concentrations may rise again. This is only a speculative suggestion and there is no long term monitoring to confirm either way, but it does suggest that the long term benefits of cavity washing to remove the below ground contaminant load may need to be confirmed before it can be relied on as a mitigation measure. A better understanding of the post operational behaviour of leachates would help to determine whether cavity pumping and treatment is worthwhile beyond the simple fact of maintaining groundwater flow towards the reactor.

3.3 FACTORS INFLUENCING MIGRATION BEYOND THE IMMEDIATE REACTOR ZONE

The risk of groundwater pollution from UCG depends almost entirely on whether the contaminants produced can migrate beyond the immediate reactor zone to more 'sensitive' groundwater areas. The practicalities and constraints associated with assessing the risk of groundwater pollution represented by UCG are discussed within Section 4 of this report. In order to understand and implement the practicalities, it is first necessary to understand the theory behind the mechanisms that govern the movement of contaminants beyond the immediate reactor zone to the wider groundwater environment.

It is extremely difficult to predict the exact volume and concentration of emissions from the gasifier, but results from previous trials do give an indication of pollutant transport mechanisms. It is important to note that the operational controls available at depth mean that it should be possible to mitigate against emissions during gasification. However, in order to gain regulatory approval it is likely that a 'worst case' scenario that assumes some

gas escape during operations will have to be evaluated. For simplicity, emissions have been separated into gas escapes and leachates in the following discussion, however interactions between the two contaminant types are also discussed where appropriate.

3.3.1 Gas Transport Mechanisms

There are a number of potential mechanisms for gas transport through a water saturated porous medium. The theory behind these is discussed in Appendix D. Although there are large uncertainties over the gas flow mechanisms that have contributed to pollution events in previous trials, transport of gases as a free phase by displacement of pore water in the rock matrix appears to be the only mechanism that would provide sufficiently rapid gas transport to cause the contamination effects that have been observed.

Under these conditions, the gas is 'driven' in its gaseous form by the difference between the pressure regime in the reactor and hydrostatic conditions in the rock matrix. This pressure differential enables the migrating gas front to 'push' groundwater out of fissures and fractures in strata, allowing the front of the gas body to migrate rapidly through the strata.

A conceptual illustration of the factors influencing the preferred route and extent of migration of a 'free phase' gas escape on a microscopic level are illustrated in Figure 3.5. Broadly speaking this means that gases will tend to flow up-dip or through vertical fissures until the increasing pore pressure creates an equilibrium with the buoyancy vector and the difference between the gas pressure and the hydrostatic pressure.

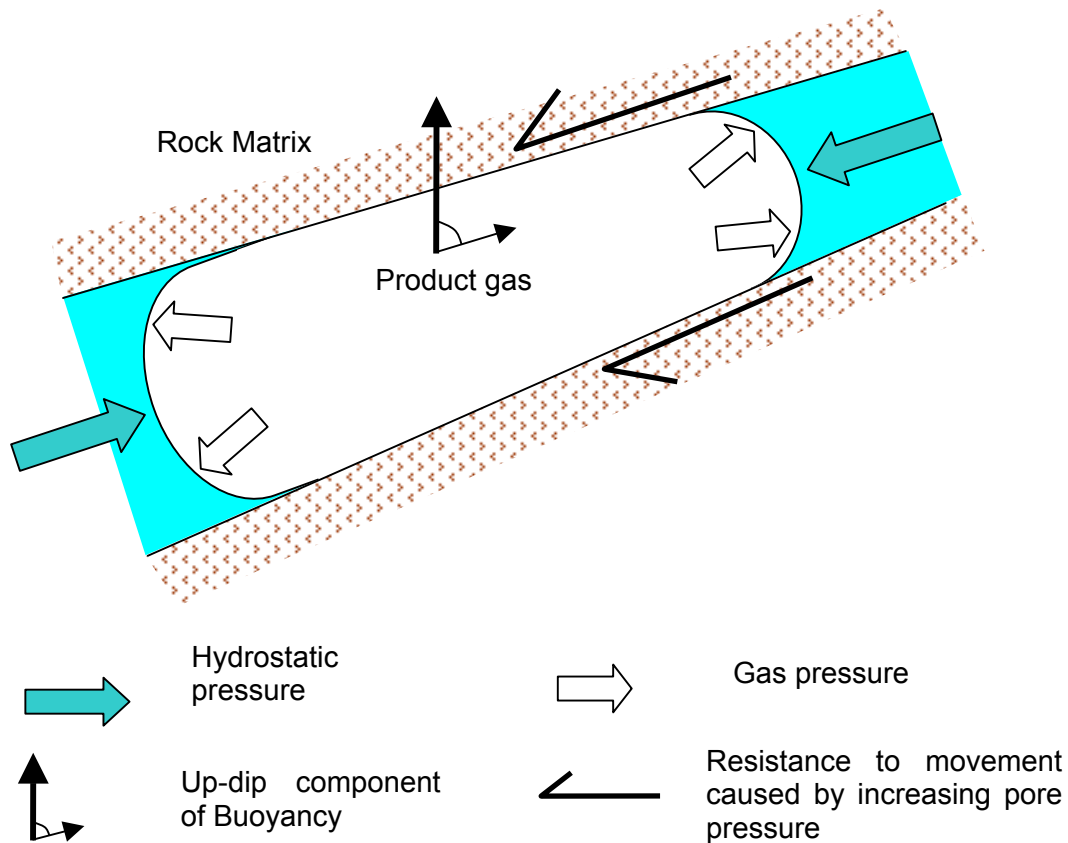


Figure 3.3 - Suggested Conceptual Illustration of the Forces Affecting Gas Movement Underground in Saturated Strata (courtesy of WS Atkins)

Figure 3.3 is a simplification of the mechanism. There are important theoretical differences between this and slower moving Darcian dual phase flow equations, as discussed in Appendix D.

Overall, the theory stipulates that if product gases do migrate beyond the gasification reactor they will tend to flow upwards due to their buoyancy, irrespective of the direction of groundwater flow, as the 'driving force' is associated with excess pressure within the reactor. The relative transmissivity of the surrounding strata is important as gases will tend to move preferentially through open fissures, fractures and other structural underground features. Except where vertical fissures exist, lateral, up-dip movement (rather than vertical movement) is likely to predominate due to the general lack of continuous vertical transmissivity within strata around the coal seam (this is usually simply due to the fact that coal overburden tends to be laid down in horizontal, cyclic beds with interbedded impermeable layers).

The distance that gases migrate will depend on:

- the resistance to flow offered by surrounding strata. Surface tension (capillary pressure) within groundwater in coherent strata can be

sufficient to prevent displacement and hence migration of gases. The pressure required to overcome this has been referred to as 'critical pressure' (Rodwell *et al*, 2000b), as discussed below; and

- the continuity between the escaping gas body and the UCG reactor. If gas pressure reduces locally, then groundwater may migrate back into some of the fissures along the flow route. Once gases are 'cut off' in this way, then their pressure will tend to reduce as they expand and an equilibrium is reached with hydrostatic pressure. This will help to reduce the distance of migration, although up-dip movement due to effective buoyancy may still be a factor. This means that long, continuous episodes of elevated reactor pressure are likely to be more significant than short, fluctuating changes.

The second point is potentially very important to UCG. Even in a 'worst case' scenario, gas escape is likely to be short lived and hence intermittent. Therefore driving pressure is unlikely to be maintained for long periods of time, thus limiting the distances over which the gasses can move.

Overall, modelling of gas transport in the geosphere is very complex and is not well understood. For the purposes of UCG, the simplest method for estimating the extent of gas migration may be to look at areas of strata where the 'critical pressure' threshold is likely to be high enough to prevent gas flow. Some examples of 'critical pressures' are given in Rodwell *et al* (2000b), but generally speaking a solid, unfaulted, cohesive mudrock (or possibly siltstone) will require a critical pressure above 1 MPa (10% of a 100 bar reactor pressure).

The rate of flow of gas is obviously also important, as gas pressure will only be elevated above hydrostatic for relatively short periods of time. Theoretically, aperture width is a reasonable indicator for potential flow rate, but obtaining in-situ aperture data and hence modelling the speed of gas transport is likely to be extremely difficult. Estimates of the permeability of rocks to gas flow can be made by using equations provided in Appendix D. If gas permeability assessments based on hydraulic properties are to be used, then assessors are referred to standard petroleum engineering texts (eg Dake, 1998). However, care should be taken that the difference between reactor and hydrostatic pressure is also allowed for. As discussed above, this may create a stepped change in pressure at the gas front, rather than the simpler general pressure gradient used in most petroleum engineering analysis.

It is important to note that because of the nature of free phase gas flow, aqueous phase contaminants can become 'entrained' within gas escapes. Gases will also dissolve in groundwater, leaving an aqueous phase contamination 'signature' where gases have passed through strata. These mechanisms are discussed in Appendix D. It is thought that entrainment of organic leachates within gas escapes as they passed through the pyrolysis

zone were responsible for many of the contamination events encountered in previous trials.

Complex models have been developed for gas transport, particularly in association with the Nirex project. However, such models require detailed knowledge of the geology and hydrogeology in-situ, based on very extensive site investigations. Therefore it is suggested a more practical approach is required that allows for the transport mechanisms discussed here, but that relies on a semi-quantitative risk based analysis.

3.3.2 Aqueous Phase Contaminant Transport Mechanisms

The transport of aqueous phase contaminants beyond the immediate reactor zone depends on the geological setting of the gasification reactor and the hydrogeology of the area.

As noted previously, the concentration of organic compounds from tars and oils in the char zone depends on the balance between leaching and adsorption in the coal. Because of this balance and the fact that some of the potential contaminant load will be 'washed' into the reactor during the gasification process, it is extremely complicated to try and estimate the concentration of leachates that would migrate beyond the pyrolysis zone. The same principle applies to inorganic leachates and dissolved contaminants that also rely on leaching or phase transfer. Practical approaches to this are discussed in the Best Practice Guidance Document.

Simple leaching of contaminants from the reactor during operations is unlikely as hydrostatic conditions will tend to promote groundwater flow towards the reactor. However, as noted above, dissolved contaminants from the reactor and pyrolysis zone can become entrained within gas escapes if hydrostatic pressure is exceeded during operations. Therefore, where gas escapes have passed through strata, this can leave a 'deposit' of acidic, high sulphur/chlorine water containing dissolved ammonia and leached organics some distance from the reactor. Actual groundwater movement during operations is still likely to be towards the reactor, so further movement of these contaminants away from the reactor beyond the extent of the gas escape is unlikely until the post-gasification hydrostatic regime has been established (unless gas escapes move beyond the confines of the operational cone of depression).

During previous studies, many of these contaminants have been pulled back into the reactor at the end of the process as pressures in the reactor are lowered during venting. This indicates that contaminants that have been released during gas escapes have migrated back towards the reactor, which is logical if groundwater flow is maintained towards the reactor.

Modelling of aqueous phase transport once pre-operational hydrostatic conditions are re-established after UCG operations is based on conventional

groundwater contaminant migration theory. This is discussed within Appendix D, but essentially relies on Darcian flow (hydrostatic pressure gradients and rock mass permeability) and the attenuation of contaminant concentrations as they are diluted by groundwater and interact with the rock mass.

4. EVALUATION OF THE RISKS TO GROUNDWATER

4.1 OVERVIEW

Although the risks to groundwater at a suitably selected site are likely to be low, regulatory constraints and public perception mean that evaluation of the risk of groundwater pollution is likely to be a key element any successful UCG operation. A suitable site selection process (where key hydrogeological attributes are compared to assess suitability) and planning application/environmental impact assessment (EIA) are required both to gain appropriate authorisation and to prevent groundwater pollution. Because of the complexities of the underground environment and the contaminant transport mechanisms involved, the evaluation of the pollution risk to groundwater needs to be both technically robust and practical.

Understanding the risk presented by contaminant production and transport mechanisms requires an evaluation of geological and hydrogeological factors at the site. A key parameter that also defines the risk in a UK context is the regulatory regime for groundwater. This is discussed in detail in Section 7, but the key issue is that it is unlikely that any significant migration of contaminants beyond a pre-defined PU groundwater zone will be permitted at a UK site. The definition and legal status of the PU zone is discussed in the regulatory section of this report, but it is essentially 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'. The PU zone means that, in a UK context the assessment of the pollution risk should be geared towards examining the possibility that significant quantities of contaminants will migrate beyond this zone to overlying (or even underlying) aquifers. This significantly influences the approach to contaminant transport modelling, as discussed later.

This section concentrates on the practical application of the theory and understanding of UCG contamination provided in earlier sections to provide a meaningful assessment of the risk to groundwater in a deep UK environment.

In order to evaluate the influence that UCG has on groundwater, it is considered that a number of stages of analysis need to be followed. In broad terms these can be divided into the following stages:

- review the potential underground pathways that can allow these contaminants to migrate to aquifers that are economically or ecologically significant;

- examine the effect that human activities can have on these potential mechanisms;
- evaluate the risk that contaminants could migrate beyond the PU zone in significant enough quantities that may cause concern to the regulators; and
- review the potential risks of surface activities to groundwater.

4.2 POTENTIAL CONTAMINANT MIGRATION PATHWAYS BEYOND THE REACTOR

Most 'potentially suitable' sites are likely to have a significant thickness of Coal Measures or later Carboniferous strata between the target seam and overlying 'significant' aquifers. This means that the general groundwater environment around the target seam will be heavily dominated by very low permeability mudrocks (shales, seatearth, mudstones etc). The nature of these strata is discussed in Appendix E, but the key impact on risk evaluation is the fact that the overall nature of the surrounding strata provides a low risk environment in terms of contaminant transport.

This means that evaluation of the risk of contaminant transport beyond the reactor zone, needs to be geared towards identifying and assessing realistic pathways through which transport can occur underground. These must be relevant to UK Coal Measures horizons and must present a pathway that allows transport in a meaningful timescale (ie one that may have an influence on the regulatory process discussed later in this report). The risk of contamination presented by these pathways has to be combined with 'induced' pathways that result from changes to strata conditions (particularly the strata relaxation caused by the caving of the gasification reactor).

4.2.1 Migration Pathways for Gaseous Contaminants

As noted previously, deep UCG operations are reasonably controllable and even in 'worst case' scenarios gas escapes are likely to be short lived unless there are serious errors in mass balance calculations and other real time controls. The theory presented earlier means that gases are likely to move rapidly and preferentially through joints, fissures and other openings in the rock mass. Therefore matrix permeability of the surrounding strata is relatively unimportant except in high permeability, fissured rock masses (eg the Sherwood Sandstone, where bulk transmissivity is strongly influenced by joints and fissures, but where the rock matrix itself is also permeable and allows fluids to flow between joint sets).

On this basis, the main potential gas migration pathways to be considered include natural and manmade fractures within strata surrounding, or adjacent to, the UCG reactor. These include:

- fractured, transmissive sandstone horizons;
- joints, cleat and slips in coal;

- faulting;
- igneous dykes and sills;
- karst formation in limestone and collapsed formations caused by dissolution of evaporitic deposits;
- joints, fracturing and bed separation induced by reactor caving or nearby mining activities; and
- abandoned boreholes.

Details of the implications that these strata types have on the risk of contamination are discussed as part of the overall risk assessment, but a description of each potential pathway is given below.

Sandstones are the most obvious potentially transmissive horizons within Coal Measures and other Carboniferous strata, although the degree of fracturing and permeability is highly variable. This is discussed further in Appendix E.

Joints and cleat are rock fractures within coal normal to bedding planes resulting from the compaction of sediments usually forming two sets that are orthogonal. Slips are confined within the coal seam boundaries and are fractures that dip commonly 40-50°. Gas flow through coal seams is thought to be one of the most important mechanisms for contaminant transport in previous shallow trials. However, the increased confining pressure at depth means that this may be much less significant for a deep UCG trial site. Further information on the permeability of deep coals is provided in Appendix E.

Faults may be defined as a structural discontinuity along which there has been significant displacement. This results in the movement of strata bodies relative to each other and can result in transmissive systems of fissures in the fault plane, which can be very important contaminant migration pathways. These are discussed further in Appendix E.

Igneous sills and dykes transgress some coalfields, markedly affecting coals by the heat of the intrusion. Coal rank increases towards the intrusion and natural coke forms against the igneous rock (Johnson, 1995). Water-filled cavities have been encountered in igneous dykes of Tertiary age when coal mine roadways have driven through them (Randall and Jones, 1966). Joint systems within the dykes together with cavities have provided a direct water migration route from overlying Coal Measure and Permian aquifers.

Karstic structures occur in carbonate rock types. The term 'karstic' refers to strata where groundwater has caused dissolution of the rock along fractures, joints and bedding planes that has increased the size of these features and significantly increased the bulk transmissivity of an otherwise impermeable rock mass. Similar processes can occur if water is introduced to evaporitic rocks where dissolution can be extensive and more rapid than in limestones.

The caving induced by the collapse of the reactor or nearby mining activities leads to strata relaxation that can significantly increase the occurrence of joints, fissures and bed separation in affected strata. This is further discussed later in this section and in Appendix F. Boreholes and shafts associated with mining can also provide open pathways that promote the rapid vertical movement of contaminants.

4.2.2 Migration Pathways for Aqueous Phase Contaminants

Migration of aqueous phase contaminants (leachates, dissolved gases etc) will be affected by similar rock mass properties to gas flows, but is a longer term issue that will rely more on the matrix permeability of the strata in which it is flowing, as well as fissures, joints and faults. In Coal Measures geology this is likely to be dominated by sandstones or siltstones, as discussed in Appendix E. Structural features such as faults are also likely to play a significant part in local flow regimes.

The main difference between gaseous and aqueous contaminant transport is the fact that the direction of transport will be strongly affected by the direction of groundwater flow, unless flow rates are extremely low, in which case diffusion due to concentration gradients may be important. Generally speaking this means that, even if potential contaminant pathways are identified that could allow aqueous phase contaminants to migrate towards overlying (or underlying) aquifers, the direction of groundwater flow must allow migration through these pathways. For instance, if a fault is identified as potentially transmissive, an upwards pressure differential must exist between strata at depth and overlying aquifers before the fault will transmit contaminants from the target seam level to the overlying aquifer.

Hydrogeological evaluation of this sort may be very difficult as there is generally very little hydrogeological information available at depth. Further guidance on hydrogeological evaluation is provided later in this report.

4.2.3 Induced and Modified Migration Pathways

Human activities can have a large impact on contaminant migration pathways at the site. These activities can cause existing migration pathways to become more permeable, or can even provide new pathways through which potential contaminants associated with UCG can migrate. The main impacts that need to be considered in terms of contaminant migration are:

- the collapse of the UCG reactor itself;
- mineral workings and resource extraction activities such as Coal Bed Methane extraction; and
- deep site investigation boreholes and wells.

Strata Response to UCG

There are a number of approaches that can be used to estimating the impact of the caving of the UCG reactor on local strata permeability. These are largely

based on knowledge gained from conventional coal mining and are discussed in Appendix F. In simple terms, strata relaxation increases permeability by reducing the confining pressure placed on rocks, which in turn allows cracks and fissures in the rock masses to widen. In certain zones above the workings the strata relaxation can lead to tensile strains, which can create new cracks and fissures in the rock mass.

Whilst the strain placed on rock masses due to caving can be estimated with a reasonable degree of accuracy, the effect that this has on permeability (particularly in relation to gases) is not as certain. It is therefore suggested that a conservative approach needs to be adopted to UCG developments. Since the amount of strain placed on the rock mass is indicative of the level of increased permeability, assessing the maximum extent of low 'limiting strain' values (eg 1 mm/m) can give a good indication of the maximum extent of the cavity on strata permeability. Applying factors of safety to the guidelines used for preventing mine inflows may also provide a valuable estimate of the extent of the impact. Both of these approaches are discussed in Appendix F.

Results from the analysis contained within Appendix E provided the following provisional conclusions about strain values above a UCG reactor. Applying Appendix E methods to the case of a 50 m wide by 250 m long isolated gasifier indicates that the 'inflow' limiting strain (5 mm/m) at the base of an aquifer will not be exceeded unless the aquifer is situated in the immediate roof of the gasifier. For smaller limiting strains, 1 mm/m is encountered at 2.5 M and 0.5 mm/m is encountered at 5 M. This is effectively the height of the caving zone for a mine roadway, so for a single reactor, the height of the caving zone should effectively represent the maximum extent of significant strata impacts (this assumes 'typical' Coal Measures strata with no significant impacts due to the thermal shock of gasification). This confirms the original supposition that a narrow single reactor behaves in a similar fashion to a collapsed mine roadway.

In the case of the envisaged 250 m by 250 m multiple gasifier panel with a 2.5m seam, the required minimum thickness of strata between the aquifer and the gasifier are as shown in Table 4.1.

Limiting Strain Criterion	Strata Thickness
10 mm/m	6 M (15 m)
5 mm/m	12 M (30 m)
1 mm/m	60 M (150 m)
0.5 mm/m	120 M (300 m)

Table 4.1 - Minimum Thickness of Strata between the Aquifer and the Gasifier for a Multiple Gasifier Panel.

This assumes that there is a pillar of coal left between the reactors and the overburden consists of 'typical' Coal Measures. In this case, the National Coal Board (NCB) criterion of 45 m Carboniferous strata (discussed in Appendix E) is more onerous than the 10 mm/m or 5 mm/m limiting strain criterion that has been used for estimates of mine inrushes.

Overall the impact of the caving of the UCG reactor on surrounding strata and the resulting risk to groundwater will depend on the following factors:

- the width and number of reactors involved;
- the location of strong, competent strata layers that may arrest upward development of strain and create 'subsidence' effects beneath them;
- the location, nature and geometry of faults; and
- the proximity of strata effects to assessed potential contaminant migration pathways.

Any assessment of the impact that caving has on the risk of contaminant escape therefore has to be considered in relation to the wider geology and risk assessment at a site. The information in this section can then be used to make a 'best guess' of the significance of the reactor caving in combination with the wider hydrogeological knowledge of the site.

As the effect of relaxation on permeability is not certain from these methods, it may be necessary to adopt more novel approaches to assessment if strata relaxation is thought to be a key issue at a particular site. Recent developments in the petroleum engineering industry mean that 'coupled' models are available that relate the stress caused by hydrocarbon extraction to changes in permeability in the hydrocarbon reservoir (Smart, 2003). This requires standard reservoir engineering support field data such as core permeabilities, factors for 'upscaling' core samples to regional permeability values and allowances for discontinuities and faults.

These more novel approaches are not yet common practice, but they are based on standard tools and are becoming more widely used. However, application to situations such as UCG or longwall panels are not yet proven and, whilst there is theoretically no reason why they cannot be applied, the focus of such models has been on larger scale applications relating to fluctuations in fluid pressure, rather than discrete void spaces. Such accurate models also require a good understanding of the rock mechanics for the given area, which may not realistically be available for a trial or semi-commercial UCG operation. Therefore it is suggested that further research in proving the applicability of the approach to UCG would be required before this could be recommended as 'best practice' for site investigations.

In relation to surface subsidence, it is highly unlikely that a single narrow reactor at depth will result in any detectable surface subsidence. The development of panels comprising multiple gasifiers for the semi-commercial

scale operation may give rise to limited surface subsidence, but the layout of such panels can be planned to minimise any adverse effects. The design of such layouts and the estimation of the resulting subsidence profile can be carried out using the empirical methods developed for longwall coalmines provided in Appendix F.

Adjacent Mineral or Gas Production Activities

Any pre-existing mine workings close to the site will also have disturbed the natural rock fabric within and adjacent to the areas mined, resulting in the same extension of natural joints and the formation of mining induced joints as discussed for reactor

Mines will normally be at some distance from the UCG reactor, so 'rules of thumb' may be used to determine potential interference with contaminant transport pathways. The zone of extensional stress from longwall workings generally extends upwards and outwards from the edge of the workings to the surface at an angle of approximately 35°. Thick competent beds in the overburden can prevent the full effects of subsidence reaching the surface and lead to bed separation. The de-stressed zone around mineworkings extends for up to 200 m above and 70 m below the workings (Creedy, 1991) and for a distance of about 20 m horizontally from the workings (Dunmore, 1969). The proximity of large faults to the mine workings can lead to the concentration of subsidence along the fault plane and extended associated joints.

As well as affecting the transmissivity of strata, coal operations up-dip of UCG may change the groundwater regime. Operational coal mines are de-watering Coal Measures so that the reduced piezometric head extends well beyond the mine workings, but negative pressure exerted on the mining system for ventilation purposes only extends as far as the zone of mining influence around the workings. CBM operations also modify groundwater levels but only within the area that is local to operations themselves. Abandoned Mine Methane (AMM) operators apply only relatively low negative pressures at the surface vents, and these effectively reduce with increasing distance from the vent because of frictional losses. Water levels in abandoned mine workings are rebounding within the extensive areas that were historically de-watered.

Although coal mine and AMM operations apply negative pressures to the system the effects are limited to the zones of influence extending to an envelope of approximately 200 m x 70 m x 20 m around the workings. Coal mine and CBM operators actively reduce the hydrostatic pressure around their operations to extents that are presently undefined.

Overall therefore, the 'rule of thumb' used in UK site selection of a minimum distance of 500 m between UCG operations and existing mineworkings appears to be adequate, although care should be taken to allow for potential inaccuracies or omissions from old mine plans.

Boreholes and Wells

Boreholes and wells can perhaps represent one of the most significant risks of contaminant migration in low permeability conditions. This includes the injection and production wells and any investigation boreholes drilled for the UCG site investigations

Conceptually the risk from wells and boreholes is simple. They must be suitably cased through permeable horizons to ensure that groundwater or gases cannot enter the borehole and there must be a good seal between the borehole and the rock within those horizons to ensure that there is no gas or groundwater migration along the outside of the borehole.

The construction of boreholes for the UCG development is an engineering issue and is covered in the Best Practice Guidance Document. However, other monitoring boreholes or abandoned site investigation boreholes may not have been constructed to appropriate standards. Such boreholes can also cause aquifer cross-contamination, which although this will have been already present before UCG operations started, may be significantly exacerbated by the hydrogeological changes caused by the UCG reactor.

Because the risk posed by individual boreholes depends on the method of construction, it is almost entirely site specific. Where there are concerns over the construction or condition of a pre-existing borehole, then remedial engineering such as grouting may be required.

Abstraction boreholes in the area will lower groundwater head in the relevant aquifer. This may be significant because the cone of depression caused by the abstraction borehole may cause a difference in hydrostatic head between surface aquifers and deeper groundwater that can promote upwards groundwater flow.

4.2.4 Contaminant Migration Pathways Associated with Surface Spills

The nature of surface spillage risks mean that the potential impact to groundwater of leaks and spillages at the surface will be heavily influenced by engineering design and site operation procedures. The most significant 'natural' factor that will vary from site to site is the groundwater vulnerability classification, as described in the Environment Agency's document 'Policy and Practice for the Protection of Groundwater'.

4.3 GEOLOGICAL AND HYDROGEOLOGICAL EVALUATION

This section provides guidance on assessing hydrogeological and geological attributes of the site that can be used as the basis of the assessment of groundwater risk presented by UCG.

In simple terms, the evaluation of geological and hydrogeological characteristics in a typical deep, low risk environment requires two main activities:

- identifying the main potentially transmissive features and potential links between them that could provide a continuous transmission pathway beyond the PU zone; and
- determining whether hydrogeological conditions are likely to promote transmission of contaminants through potentially transmissive features.

This will require a good understanding of the geology and conceptual hydrogeology at a site, supported by desk study and site investigation data.

The theoretical mechanisms of gas and liquid transport have been analysed in detail earlier in this report. In practical terms, for gas transport, there are two key factors that need to be borne in mind:

- flow is likely to be up-dip or vertical. The groundwater flow regime is largely irrelevant, but the hydrostatic pressure in various strata layers during operations is important; and
- calculation of flow rates etc is likely to be extremely difficult because of the nature of gas transport through the geosphere. Therefore a risk based approach centred on the presence of low permeability, relatively unfaulted and un-fissured rocks is advised.

The analysis of aqueous phase contaminants will be more time dependent. Flow will be dictated by hydrostatic conditions, rather than by buoyancy. This means that the assessment may require estimates of:

- the amount of drawdown caused by the removal of groundwater during the process in the coal seam and the impact on key permeable horizons;
- the rate of recovery of hydrostatic conditions after operations have ceased and the potential impact of post operation cavity pumping; and
- groundwater flow rates through key transmissive strata and structural features once equilibrium conditions have been restored. This may not be the same as pre gasification conditions due to strata relaxation impacts discussed earlier.

An overview of the suggested process for evaluating technical parameters relating to gas and leachate transport is given within Figure 4.1. The quality of the evaluation will depend on the data available and it is designed to be iterative, so that it can be updated as more information is available.

Whilst it is impossible to generalise about the type of hydrogeological regime that may be present at a site, it is worth noting that deep hydrogeology can demonstrate features that are not found in more 'conventional' hydrogeological assessments. When evaluating deep hydrogeology, there

may a number of distinct groundwater 'zones' where the rate and vertical component of flow differs. Often this will consist of a relatively rapid moving upper aquifer zone that interacts with surface recharge and discharge and a slower moving zone beneath that with minor flows. Where distinct layers exist, then there will often be hydrochemical differences in the various groundwaters.

Where flow rates are distinct, then potential head differences can arise in different layers of strata. This may not be significant due to hydraulic separation of strata layers, however it can be important in fault zones where increased permeability can allow movement between otherwise distinct 'zones'. Evaluation of the hydrogeological regime requires a wide variety of technical skills that cannot be described within the scope of this report, so this section concentrates on the overall framework for the assessment and suggested guidelines for interpreting the factors.

4.3.1 Guidelines on Geological Attributes

The previous section provides a framework for the evaluation of the geology and hydrogeology at a given site. These must be applied to the site based on specific information about:

- lithology (the nature of the rock layers);
- structural geology and rock masses (structural controls that have resulted in fractures, fissures, faults etc); and
- hydrogeology.

Any evaluation will be necessarily site specific and should be based on appropriate desk studies and site investigation techniques (including those discussed in the Best Practice Guidance Document). However, there are some general geological characteristics that have been investigated as part of this study that can be used to inform the geological evaluation and risk analysis process. These are discussed in Appendix E and relate to:

- controls on the permeability of coal seams;
- the nature and transmissivity of Coal Measures rock and rock masses; and
- the nature and potential transmissivity of faults.

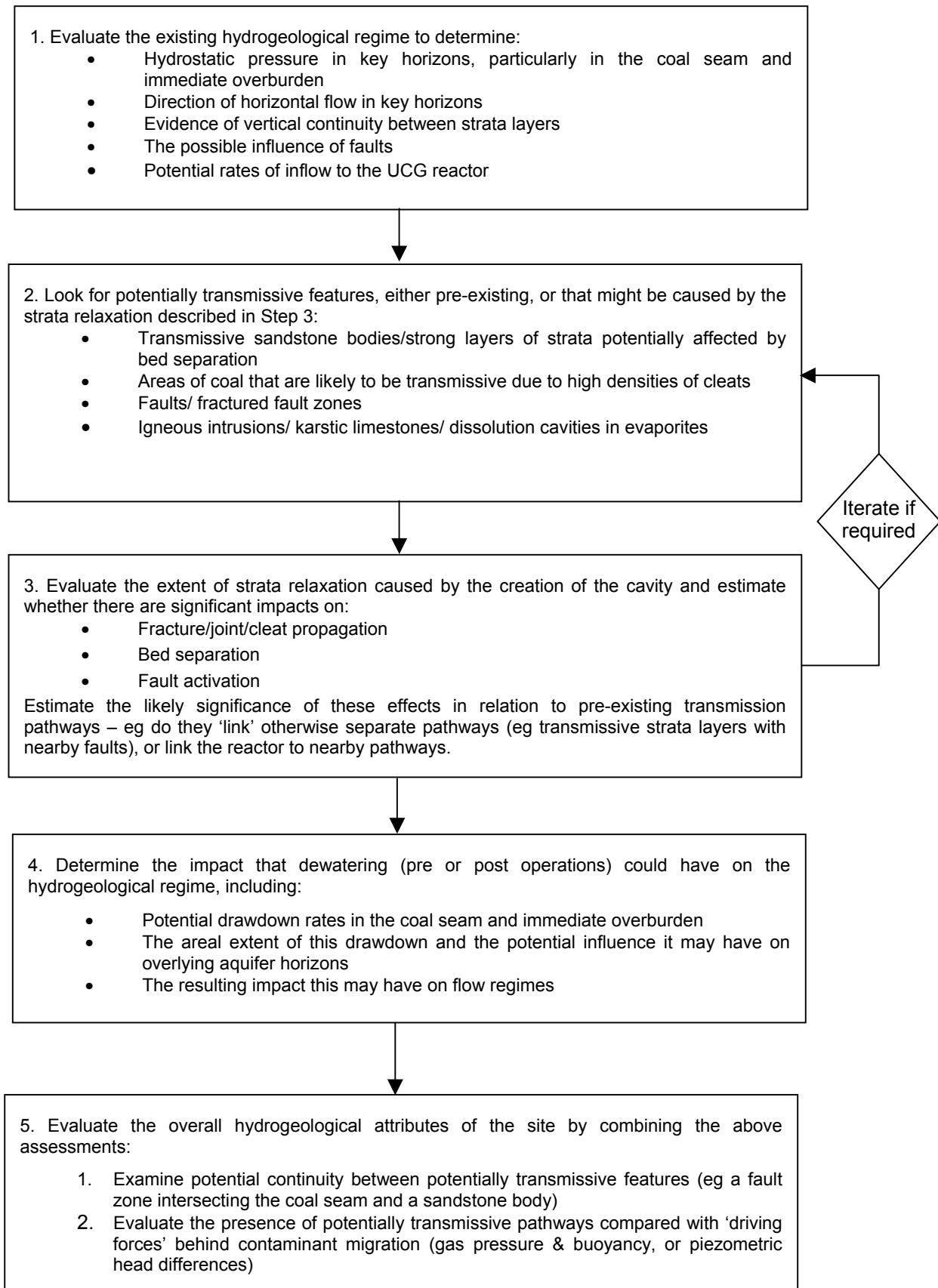


Figure 4.1 - Concept for the General Hydrogeological Evaluation Process (courtesy of WS Atkins)

4.4 GROUNDWATER RISK EVALUATION

4.4.1 General Approach

Although an understanding of the geology and hydrogeology at a site will form the basis of any risk assessment, a wider structure that incorporates the purpose, requirements and practicalities of the risk assessment needs to be allowed for in order to provide a meaningful assessment.

General risk assessment theory describes the significance of the risk from the following elements:

- hazard –primarily the gaseous emissions and leachates described previously, with a secondary hazard of ‘cross contamination’ of aquifers;
- hazard-receptor pathways – these ‘contaminant migration pathways’ have been discussed in previous sections;
- likelihood of occurrence – for UCG, this represents the probability that the contaminant in question will escape beyond the PU groundwater zone. The likelihood should incorporate connectivity between contaminant pathways, direction of groundwater/gas flow and timescales involved in contaminant migration; and
- consequence of occurrence - this represents the impact that the contaminant will have if it does enter ‘sensitive’ aquifers. Generally speaking this will be an ‘absolute’ once the PU zones has been defined – ie a significant likelihood of migration beyond this zone is not acceptable. However, the risk consequence can impact on the definition of this zone and can help to determine the requirements that will be placed on the monitoring regime.

Although the effective prohibition of contaminants beyond the PU zone places constraints on the risk assessment, the concept of hazard-pathway-receptor is still a useful concept to bear in mind whilst carrying out the assessment.

The main component of risk that varies from site to site is the likelihood of contamination, which is based on the geological/hydrogeological evaluation discussed above. This will form the bases of any site comparison or EIA, but a time based element is also required in the assessment to determine if concentrations will still be measurably above baseline conditions by the time they reach ‘sensitive’ aquifers (ie there is an element of ‘consequence’ involved).

It is suggested that a risk assessment should be based on an iterative approach such as the one illustrated in Figure 4.2. This proposes a staged approach that starts with simple assessments of potential risk pathways, but with conservative assumptions. If there appears to be a risk, then the detail of the analysis is increased to determine the level of the risk. This means that

investigation can be targeted towards the end result, which could range from a comparison of the suitability of the sites, to providing sufficient evidence to the regulators that there is a negligible risk of contaminant escape beyond a defined zone at the site.

There are practical planning advantages to such a staged approach. As it may be necessary to apply for planning permission prior to site investigation boreholes being drilled, then there may be uncertainties in the geological/hydrogeological knowledge at the site at the planning stage. A staged risk approach may be able to provide a framework that provides sufficient analysis of the risk to gain conditional planning permission, which can then incorporate site investigation data if permission is gained.

4.4.2 Stages of Assessment

The approach can be adapted to the various levels of the site selection and site investigation process. For a site selection/comparison phase, it is probable that an estimate of the PU zone and identification of potential contaminant transport pathways will be sufficient to derive the comparative assessment. However, for the EIA/site investigation stage, close liaison with the Regulator will be required and more detailed analysis or modelling will be required. Site investigations will require at least three deep boreholes for operational purposes, so there should be a reasonable amount of information available for modelling purposes at this stage.

It is likely that the extent of the PU zone would have to be discussed and agreed, the 'acceptable' timescale for any contaminant transport models will have to be determined and conclusions about levels of risk from the gasification would have to be discussed and agreed before authorisation will be given. This process can also be iterative, with investigations continuing until a site is either deemed unsuitable or appropriate regulator authorisation has been obtained.

General Considerations in the Assessment of Potential Flow Paths

The first stage of assessment is to determine whether there are any realistic gas or leachate contaminant transport pathways, given the assumption that gases and leachate will escape from the reactor. As noted previously, good operational control of the reactor should be possible, so realistic 'what if' scenarios should be used to determine the 'worst case' scenarios for gas escape during operations (eg gas losses will only continue for a few weeks at a certain maximum elevated pressure).

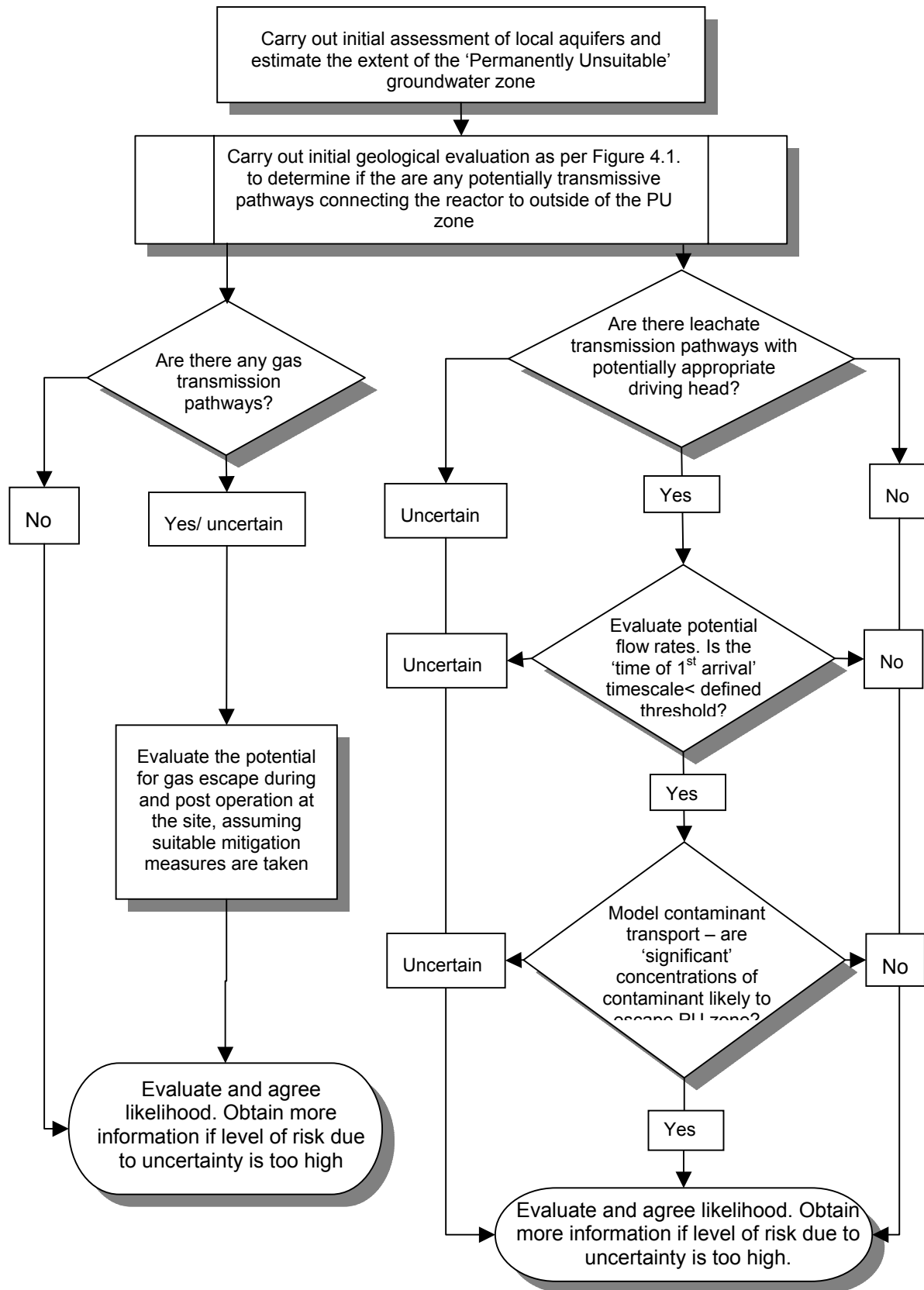


Figure 4.2 - Generic Risk Assessment Process (courtesy of WS Atkins)

Geological/hydrogeological evaluation of potential flow paths has been discussed previously, but typically the first phase will comprise of elements such as:

- a review of the nature and extent of nearby faults and their susceptibility to dilation caused by strata movement associated with the reactor;
- identifying uncemented or fractured sandstones and the likelihood that these would be intersected by the zone of caving associated with the reactor;
- assessing the potential gas permeability of the target coal seam and the risk presented by up-dip flow from the reactor; and
- a review of the consistency and extent of mudrock layers and whether there are any zones of thinning strata that may allow contaminant transport between more permeable horizons.

It is very important to note that a lack of contaminant transport pathways must be 'actively' proven. It is unlikely that an assessment will be deemed to be satisfactory if the evaluation shows there are no potential pathways simply because of the fact that structural and lithological information is unavailable for much of the geology in the area. If this is the case, then either further desk studies or site investigations may be required, or a conservative approach to the risk posed by these 'unknown' areas based on the evidence available may have to be adopted.

The risk of surface spills leading to groundwater contamination should be considered as part of this evaluation, but this is generally a site design/drainage engineering issue rather than a risk that has to be dealt with by suitable site selection. Particularly vulnerable sites will raise the risk of groundwater contamination, but this is likely to be a minor consideration compared with the risk from the reactor.

Further Analysis for Gas Migration

If potential gas migration pathways are identified, then it will be difficult to determine the realistic extent of gas migration within these pathways during the time of a gas escape. The assessment may be refined to include operational issues such as tighter gas monitoring and more stringent shut-down criteria if gas escape is detected. Alternatively, a 'sense check' may be carried out based on high level, conservative estimates of gas permeability, and maximum potential differences between operating pressure and hydrostatic head. Assessments of groundwater permeability may be adjusted to estimate gas permeability in relevant strata layers. Very long sub-horizontal migration paths (eg > 1 km) are likely to be considered to present a lower risk than shorter migration pathways. .

As noted previously, estimation of gas permeability through water saturated networks is standard practice in hydrocarbon reservoir engineering.

Mechanisms are different and concentrate on the relative permeability of oil/gas/water phases during pressure changes in the reservoir (generally speaking, gas will be coming out of solution, rather than being created and dissolving into the water phase as it moves). However, interpretation of methods from standard texts such as Dake (1994 and 1998) may be useful if estimates of gas permeabilities are required in sandstone bodies.

Where the risk cannot otherwise be shown to be negligible, empirical site investigation methods for gas permeability may have to be devised. These will tend to be bespoke methods based on the particular parameters of the site that require investigation. They are likely to provide uncertain results, and if this stage of assessment is required then the site may not be suitable for selection in any case.

Further Considerations for Aqueous Phase Contaminant Transport

Generally speaking, as the risk and level of complexity at a site increases, then so does the level of investigation that is required in order to prove that the level of risk is acceptable. This means that if there are potential leachate migration pathways at the site and the hydrogeological regime means that groundwater flow may be towards upper aquifer horizons once baseline (or near baseline) conditions are reinstated, then further modelling or operational constraints may be required.

The most simple form of modelling will be to determine the speed of groundwater flow through contaminant transport pathways is sufficient to transport groundwater originating near the reactor to beyond the PU zone within 'meaningful' timescales. Estimates of the time taken should give a good indication of the 'time of first arrival' for the contaminants. This can be based on the principles discussed in Section 3.

If there is still a potential risk then the option of contaminant transport modelling may be explored. Modelling of the transport of the contaminants that allows for retardation may show that there is a negligible risk that sufficient quantities of contaminants will migrate beyond the PU zone within 'realistic' timescales.

There are a number of packages and techniques available for modelling contaminant hydrogeology, ranging from the simple, conservative EA P20 spreadsheet, to full 3D modelling packages (MT3D, Swift etc). The selection of the package will depend on the level of risk and the investigating team's own experience and preferences. However, the most significant factor is likely to be the level of information available for the site (including the quality of the conceptual hydrogeological model) and the resulting assumptions that have to be made where information is not available. In many cases complex modelling will only require additional conservative assumptions that will not necessarily improve the accuracy of the estimates. Where additional investigation is identified, site investigators should be aware of the difficulties

of obtaining in-situ information at depth and should be reasonably confident of the benefits of the information.

Modellers should be aware of the 'unusual' conditions that are present at depth when considering contaminant transport models. These are likely to be high TDS, low oxygen environments with low microbial activity. Standard literature such as Howard *et al* (Date Unknown) or Montgomery *et al* (Date Unknown) can provide guidance but it may be necessary to assume that there is no biological degradation and that retardation is only based on chemical activity, dispersion (diffusion and advection) and sorption. The low oxygen environment should be accounted for when evaluating chemical degradation. Further notes on contaminant transport modelling are provided in the Best Practice Guidance Document.

4.4.3 Impact of Mitigation on the Risk Assessment

If the risk is deemed excessive at any stage, then additional operational controls may be considered to lower the risk to acceptable levels. Typically these would include:

- constraints on acceptable levels of estimated gas losses (with agreed shut down thresholds);
- additional groundwater monitoring and shutdown requirements; and
- maintaining a cone of depression in the groundwater around the reactor (by repeated pumping and treatment) to avoid aqueous phase contaminant transport.

For example, it may be possible to use the hydrogeological information already gained to derive a post-gasification reactor pumping strategy that will ensure that groundwater flow will be maintained towards the reactor. Agreed constraints on monitoring and groundwater quality may then have to be met before pumping ceases.

These form part of operational best practice and are discussed within the Best Practice Guidance Document, however it is important to note that their adoption should be considered in the overall context of the risk presented at the site. It is therefore suggested that such measures are considered specifically to address unacceptable levels of risk, rather than as general measures that may not be necessary for some sites.

5. SURFACE WATER ISSUES

5.1 WATER TREATMENT AND DISPOSAL

The identification of an appropriate treatment process for a wastewater is, in many cases, a complex procedure. The aim of which is either to treat the water to a suitable standard for disposal or discharge to surface water, or, if appropriate to discharge to sewer. The following stages of assessment are required:

- identify the potential volumes, concentrations of pollutants and assess the risks of all chemicals used in the process;
- identify potential options: an initial list of treatment and disposal options should be developed, these options should aim to be inclusive and assess the options for disposal to sewer; and
- select practicable options: a short list of options, tailored to the site specific issues, such as pattern of operation, volumes, nearness of neighbours, cost, potential risks of failure.

These steps are unlikely to be performed as a single pass procedure, rather as an iterative process. Assumptions may need to be revisited in the light of growing understanding of the geology of the UCG site and as ancillary equipment is specified.

Further details of the assessment process are contained within the Best Practice Guidance Document, but this section provides an overview of the principles involved in that process.

5.1.1 Wastewater Characterisation - Generic

The aims of the characterisation exercise are to identify and quantify the occurrence of any undesirable substance or quality of the wastewater. The characteristics of the wastewater that may influence the selection of a treatment technique are also investigated. Detailed characterisation studies lessen the risk of substances or discharges being overlooked. However it is a matter of judgement as to whether all the significant information has been identified and the process may be iterative. Initially the focus of the study will usually be one or two characteristics of the wastewater, for example, the potential to generate hydrogen sulphide (because of associated odour, health risks or corrosiveness), or the phenolic compounds.

Integrated Pollution Prevention and Control (IPPC) guidelines (discussed below) indicate the type of data that needs to be compiled on emissions to produce a meaningful comparison of treatment technologies.

Where settlement ponds are required, these should be considered in the potential emissions evaluation (ie potential odours, risk of leaks etc). If possible a mass balance may be performed to estimate the wastewater characteristics and to determine storage requirements.

When carrying out the evaluation, it is important to consider the potential for variation. Production may occur as batches and different products may be produced from different batches using the same equipment. Their wastewaters may have very different characteristics and changes are likely to occur when product streams are mixed. High sulphates, acids and alkali may react with cementitious pipes resulting in the possibility of eroded pipes and loss of containment. Volatile substances may be stripped in the pipe. Potentially explosive or toxic atmospheres may be generated within any existing head space.

5.1.2 Potential for Wastewater Generation from UCG

The nature of wastewater concentrations and volumes are site dependent. Previous trials described in Section 2 may help to inform the treatment process selection but can only be indicative of the potential issues to be addressed.

Generally when considering the wastewaters generated the characterisation study should assess:

- process water,
- gas treatment wastewater and
- cavity flushing/pumping water.

For process water it is anticipated that most of the water generated as the steam condenses can be returned to the cavity. There may be the need to monitor for organic contaminants such as phenols also ammonia, sulphides and salts may be an issue. If these contaminants do build up they could compromise equipment due to either depositing as scale or corrosion. Consequently, a series of in-line treatment options may be required.

Product gases containing superheated steam only are the operational ideal, with a gas temperature of 350-400°C. If mineral salts are present in the gas stream they will be in the form of finely divided solids, and could be removed from the hot gas stream by centrifuging. Chlorine (as hydrogen chloride) and ammonia will be present as gases. Both are highly soluble in water and would dissolve if steam is condensed out of the product gas stream, as hydrochloric acid and ammonium hydroxide respectively. Theoretically this could leave the water neutral but an exact balance is unlikely and neutralisation will probably be required.

The dilute salt solution could be re-injected as process water, in which circumstance the salts would be precipitated within the reactor at the point of evaporation. The salts would be re-dissolved when the reactor was flushed after gasification and may need to be treated in the wash water.

Depending on the geology of the site, the water balance of the process may be positive. Infiltration may exceed the water requirement. Although it is anticipated that the site selection procedures would reduce the risk of this condition it must be considered as an operational possibility. In terms of wastewater treatment it is anticipated that infiltration water would be primarily increase the volume of water to be treated rather than adding additional contaminants. In this circumstance, all chemical species will be dissolved essentially in the liquid water. Of most concern would be the high concentrations of phenols (500 ppm) as experienced at El Tremedal. These concentrations may be better treated using oxidation processes rather than adsorption.

It is possible that sulphites and sulphates may be present and may require treatment. This is due to the odour potential and the corrosive nature if hydrogen sulphide were to be generated in the process.

Both El Tremedal and Rocky Mountain trials showed that separated water can vary significantly and rapidly in quality. Monitoring of this change is important as, though it may not significantly impact on the treatment process selected, it may be significant in determining how the treatment process is operated.

As there is the potential to generate pollutants in the gaseous form (hydrogen sulphide, hydrogen chloride and oxides of nitrogen etc), a process will be needed to separate them. This process is likely to produce some wastewater. These gas treatment wastewaters could be odorous, and may need treatment on site to avoid odour or toxic environments, but these are part of the engineering design of the process and are not considered further here.

If cavity flushing/pumping is used either for experimentation purposes or to reduce the risk at the site, then the water used on completion of operation is expected to be the most contaminated. The organic components, including phenolics, are likely to be in higher concentration as they will not have been destroyed as the burn came to an end. If the location was susceptible to high infiltration of ground water during operation, much of the contaminant load in the reactor may have been removed prior to flushing. Therefore the wash water will not be as strong. This was clearly the case at the El Tremedal trial where the final wastewater from the cavity wash comprised much lower concentrations of pollutants. The most appropriate treatment option for lower concentrations of pollutants in this case may be the adsorption processes.

5.1.3 Permissions and Environmental Regulation

The desk study should include a detailed assessment of the permissions or consents that will be required before the UCG process will be permitted to operate.

The IPPC Directive and Pollution Prevention and Control (PPC) Regulations define the approach that needs to be adopted for process selection at the site, including any wastewater treatment options. This is discussed in Section 7 of this report. They outline the framework under which the local regulator, the Environment Agency in England and Wales, issue operating permits for industrial installations (DEFRA, 2002 and Scottish Executive, 2002).

The basis of these permits is that the operator should use the processing option which gives the smallest impact on the environment (greatest environmental protection) taken as a whole (DEFRA, 2002 and Scottish Executive, 2002). To achieve this, the Regulations require the operator to use the best available techniques (BAT) which have been established for their industry. Furthermore, BAT forms a central role in the IPPC Directive and PPC Regulations since they both provide a basis from which emission limits values (ELV) will be set and provide the principal benchmark for determining the acceptable pollution prevention and control obligations of the industrial operators (Environment Agency, 1998). Consequently it will be important to demonstrate that any treatment technique selected is the most appropriate for the specific site.

One of the options is potentially disposal to sewer. The practicability of the option will depend on the distance from a suitable sewer. The sewer and associated sewage treatment works is owned and operated by the sewerage undertaker appointed under the Water Act 1989 (now re-enacted in the Water Industry Act 1991). As such they are obliged to provide, operate and maintain the public sewerage system and sewage treatment works.

Discharge consents are issued by the sewerage undertaker to permit industries to discharge wastewater and storm water to their sewerage system. Such consents normally place restrictions on the content of such discharges. The consent must contain permission to discharge the substances that are known to be in the wastewater. The concentrations of the substances permitted by the sewerage undertaker will be dependent on the dilution available in the sewer, the type of sewage treatment process operated, the size and type of surface water that the sewage works discharges and the limits set on the sewerage undertaker by the Environment Agency.

It is anticipated that if the concentrations are as at the end of operation at El Tremedal, then pre-treatment will be required prior to discharge to the sewer. If this were to be the case it is advisable to discuss the types of pre-treatment being selected as the process may need to complement the sewage treatment process rather than duplicate it.

5.1.4 Treatment Options Ranking

The options ranking step is perhaps the weakest and least scientific step in the selection process, because often the impact data are limited or incomplete, making it difficult to compare techniques on exactly the same basis.

Additionally, the options may have different amounts of emissions in several different media ('cross-media effects'), again making it difficult to compare accurately the overall environmental impact between techniques on an equal basis. This conundrum is sometimes called 'cross-media conflict'. Consequently, comparison and ranking of the options is often an "inexact science" and an audit trail must be left so that the ranking process is open to scrutiny if there is any dispute. Further guidance on treatment selection is provided in the Best Practice Guidance Document.

It should be noted that there are likely to be significant differences between a trial site and a semi-commercial operation. The trial site may concentrate on lower capital, higher operational expenditure methods due to the uncertainties involved and the smaller treatment volumes required.

5.1.5 Potential Treatment Techniques

There are many process vendors with either unique or specialised variants of generic treatment approaches. It is impossible to review each and every technology, but Table 5.1 indicates the types of technique that may be used to treat the pollutants. Further details of the generic processes are available in Environment Agency (1998) (Effluent Treatment Techniques).

• = Designed For Purpose I = Incidental P = Poor S = Some of the chemicals represented in this group	Aerobic Biological	Anaerobic Biological	Bioaugmentation*	Powdered Activated	Powdered Activated Carbon	Zeolites	Chemical Coagulation	Lime Dosing	Steam Stripping	Air Stripping	Wet Air Oxidation	Ozone, Ozone + UV, H ₂ O ₂	SuperCritical Water	Chemelec Cell Electro	Membranes NF/SM/RO	Disposal To Sewer
SS	I	I	I	I	I	I	•	•	P	P	I	P	P		•	X
COD	S	S	S	•	•	•	•	I	I	I	•	•	•		•	X
Ammonia	•	•	•	I		•			•	•						X
Phenols				S	S	S			S	S	.	•				X
Metals	I	I	I			•	•	•						•	•	X

**Note: biological treatment methods may not be suitable due to operational difficulties, particularly a potential lack of BOD in the effluent stream.*

Table 5.1 - Potential Treatment Techniques (Developed from Environment Agency: Effluent Treatment Techniques (1998))

For sulphides, ferric chloride is potentially suitable, or hydrogen sulphide can be removed via ozonation or air stripping (although this can cause odour issues).

In accordance with BAT, detailed consideration should also include issues such as energy useage, raw materials consumption, spillage, decommissioning etc.

Detailed selection may require bench or pilot scale tests to demonstrate that the appropriate treatment performance is achievable.

It should be noted that disposal to sewer is contained within this assessment. This will require the same characterisation as treatment, but will require disposal consent from the sewage undertaker (as described previously), rather than treatment design. Tankering and disposal off site may be considered, however, this is often expensive and environmentally unsound due to noise, fuel use and spillage risks.

5.2 OTHER SURFACE WATER IMPACTS

The potential impacts to surface water sources from a UCG development depend on a number of factors:

- the type and significance of potential discharges to local water bodies. Wastewater discharges to local water courses will be subject to the appropriate consent standards as discussed above. In addition there is a secondary risk of leaks or spillages of raw wastewater or liquors/by-products from the treatment process itself. Any chemicals stored on site as part of the treatment process should also be assessed in terms of their potential environmental risk. Foul drainage disposal will also be required for workers' facilities, which may require a cess-pit that will be periodically emptied by tanker;
- whether there are any water courses or wetland habitats that are expected to receive runoff from the site. The design and protection of site drainage can strongly influence this factor; and
- the environmental sensitivity of local water courses or wetlands.

Apart from wastewater treatment facilities, the risks from accidental spillages or leaks during operation are standard to operational sites involving plant and machinery, ie the risk is from oils, fuels and cleaning/lubrication chemicals. Risks during fire fighting operations also have to be taken into account. The potential impact to surface waters from leaks and spillages will be site dependent and will be heavily influenced by engineering design and site operation procedures.

Assessment of the risks from accidental leaks and spills is relatively simple as the movement of contaminants is dictated by site drainage (direction and volume). Where drainage is to a local water course, then appropriate discharge consent will have to be negotiated with the Environment Agency or the Scottish Environmental Protection Agency. This will take into account the sensitivity of any local water course, and the Regulator is likely to pursue either a 'no change' policy (to the River Quality Assessment etc), or require suitable mitigation measures (bundling, silt traps, oil separators etc) to reduce the risk of a contaminant spill. Where the discharge is to a sewer, then authorisation will have to be obtained by the sewage undertaker and this will also require mitigation against sudden discharges of oils or chemicals.

In both cases there will also be a volumetric consideration; the environmental regulator will not want a significant increase in surface drainage in flood sensitive areas or in sensitive water courses, and the sewage undertaker will only allow certain maximum discharge volumes based on sewer or treatment works capacities. These will be based on a maximum storm event, usually with a 1 in 100 year return period.

6. CO₂ SEQUESTRATION

6.1 ROLE OF CO₂ SEQUESTRATION IN UCG

As described in Section 3, the major constituents of the product gas from UCG are CO₂, H₂, CH₄, and CO. The high CO₂ content leads to an unfavourable comparison with other fossil fuel technologies in terms of global warming potential. The implications in terms of plant efficiency of the pre-combustion removal of CO₂ are addressed in Section 8.

The recovered CO₂ could be compressed and injected into the exhausted UCG reactor, or into a seam in which the permeability has been enhanced by the relaxation of the strata overlying the reactor, for the purposes of CO₂ sequestration. Alternatively, the CO₂ may be utilised to enhance coal bed methane production.

A separate report on the status of CO₂ capture and sequestration technology has been prepared for the DTI under the IEA Greenhouse Gas R&D Programme (DTI, 2003). Those aspects which are relevant to UCG sequestration are included in the following review.

6.2 STORAGE PREREQUISITES AND MECHANISMS

The pre-requisites for underground CO₂ storage are:

- a porous and permeable reservoir rock;
- an impermeable cap rock to retain the injected CO₂; and

- preferably a depth of >1000 m so that the CO₂ is in a super-critical state, allowing a large amount of CO₂ to be stored in a relatively small volume.

Once injected, the CO₂ may be held:

- in an aqueous phase, either dissolved in brine or as bicarbonate;
- as solid minerals resulting from reaction with the formation waters and strata; or
- adsorbed onto hydrocarbons, including coals.

Dissolution of CO₂ in water is a relatively slow process and so does not contribute substantially to the capacity of a reservoir to store CO₂; however, it may help in the long term to lock up some of the CO₂. Eventually, reaction with the formation rock can lock up the CO₂ permanently. The interaction between CO₂ and hydrocarbons is being applied commercially to stimulate oil or methane recovery.

The key aspects that will determine the acceptability of CO₂ sequestration associated with UCG are:

- the security of storage; and
- the potential impact of any leakage.

Three types of reservoir are currently being considered for CO₂ sequestration:

- deep oil and gas reservoirs, possibly in conjunction with enhanced oil recovery (EOR), eg the NGGAS project which is researching the safety, monitoring and verification issues relating to CO₂ storage in an offshore depleted oilfield;
- deep saline aquifers, eg the EU funded Saline Aquifer CO₂ Injection Project (SACS) which is monitoring CO₂ injection into a deep saline aquifer in the North Sea; and
- unmineable coal seams, eg the EU funded RECOPOL trial to determine if CO₂ can be safely stored in coal seams.

The EU is also providing support to an international project which is monitoring CO₂ injection in the Weyburn oilfield in Saskatchewan, Canada.

6.3 CO₂ SEQUESTRATION IN THE EXHAUSTED GASIFIER

The sequestration of CO₂ in the residual voids of an exhausted gasifier can be compared conceptually to CO₂ sequestration in deep aquifers and/or oil reservoirs, with the distinction that the overlying strata would have been disturbed by UCG.

At depths in the order of 1000 m the CO₂ would be stored principally as a supercritical fluid. Displacement would be the dominant storage mechanism initially, forcing any water out of the reactor. Over longer timescales, dissolution and chemical reaction would become increasingly important. The CO₂ would therefore be present as a supercritical fluid for thousands of years and could be regarded as being in a 'free state' condition. In the event of a failure in the integrity of the reservoir seal, the CO₂ could be released from the reservoir.

Depending on the thickness of the impermeable strata overlying the gasifier, the caving of the immediate roof strata during gasification may have compromised the integrity of the cap rock, allowing the supercritical CO₂ to migrate from the reservoir. Due to the density of the CO₂ under these conditions (~ 500 kg/m³), the rate of migration would be slow. Nevertheless, unless the upward migration of the CO₂ was arrested by a cap rock higher in the sequence, the pressure would fall below the critical pressure and the CO₂ would 'flash' over to the gaseous phase, with an associated increase in both volume and mobility.

In addition, hydraulic fracturing of the adjacent strata can be expected if the gasifier is over-pressurised during its operational or post operational phases. Experience from oil industry suggests that, once a fracture has formed, high pressure fluids can then escape.

It is considered unlikely therefore, that sequestration in an exhausted gasifier could provide a secure long term repository for CO₂.

6.4 CO₂ SEQUESTRATION IN ADJACENT COAL SEAMS

Destressed coal seams over or underlying a gasified seam appear to offer greater potential for the safe sequestration of CO₂. Coal has twice the affinity for CO₂ than for CH₄. The injected CO₂ diffuses through the pore structure of coal and is preferentially adsorbed onto the exposed coal surfaces (approx. 100 m²/g of coal in medium to high rank coals) displacing the methane. As the CO₂ is held in the coal matrix, much less 'free' CO₂ will be present compared to storage in the exhausted gasifier.

Coals of all ranks are able to adsorb CO₂. Lignite has the potential for storing CO₂ due to its high moisture contents. Lignite deposits occur under the North Sea at suitable depths.

The porosity and permeability of the seam are key parameters in determining the suitability for storage of CO₂. The pore volume of coal seams ranges from 1 to 3% of the total volume of coal and the potential CO₂ storage by adsorption in medium to high rank coal ranges from 20 to 50 m³ (STP) (40 to 100 kg) of CO₂/m³ of coal. This compares with the 500 to 700 kg of CO₂/m³ of reservoir that could potentially be stored in an underground void.

The permeability of coal is strongly affected by the effective stress, see Section 2, Figure 2.2. The permeability of coals situated at 1,000 m depth typically ranges from 0.1 to 10 mD depending on the coal rank and mechanical conditions of the seam. Initial trials of CO₂ storage in the USA were carried out in very high permeability seams. Seams in the UK generally have low permeabilities and virgin seams are therefore less attractive for CO₂ sequestration.

Also, the adsorption of CO₂ can cause swelling of the coal matrix resulting in a reduced permeability around the injection well area. The EU funded ICBM project is studying the basic science of CO₂ storage in coal seams in order to model and assess the storage potential of coal seams.

However, the relaxation of coal seams over or under-lying an extensively gasified seam arising from the stress redistribution can substantially increase permeability of the seams (Section 4) enhancing the capacity of the seams to store CO₂, and to release CH₄.

The combination of the increased seam permeability associated with UCG and the displacement of CH₄ by CO₂ injection offers the potential to partially off-set the cost of CO₂ sequestration by enhanced coal bed methane production.

This concept is illustrated in Figure 6.1 taken from a theoretical study carried out at TU Delft. The model focussed on Enhanced Coal Bed Methane (ECBM) recovery but a similar technique could be applied to the CO₂-Enhanced Coal Bed Methane (CO₂-ECBM) recovery combining CH₄ production and CO₂ sequestration. Phase 1 illustrates the situation prior to UCG, Phase 2 illustrates the gasification phase with the subsequent relaxation of the overlying coal seam, and Phase 3 illustrates the exploitation of the overlying coal seam, in this case for CH₄ production, but CO₂ could be injected following gasification to enhance subsequent methane production. Figure 6.2 demonstrates the enhancement of seam permeability associated with UCG.

Trials of CO₂ ECBM have been conducted in Alberta, Canada.

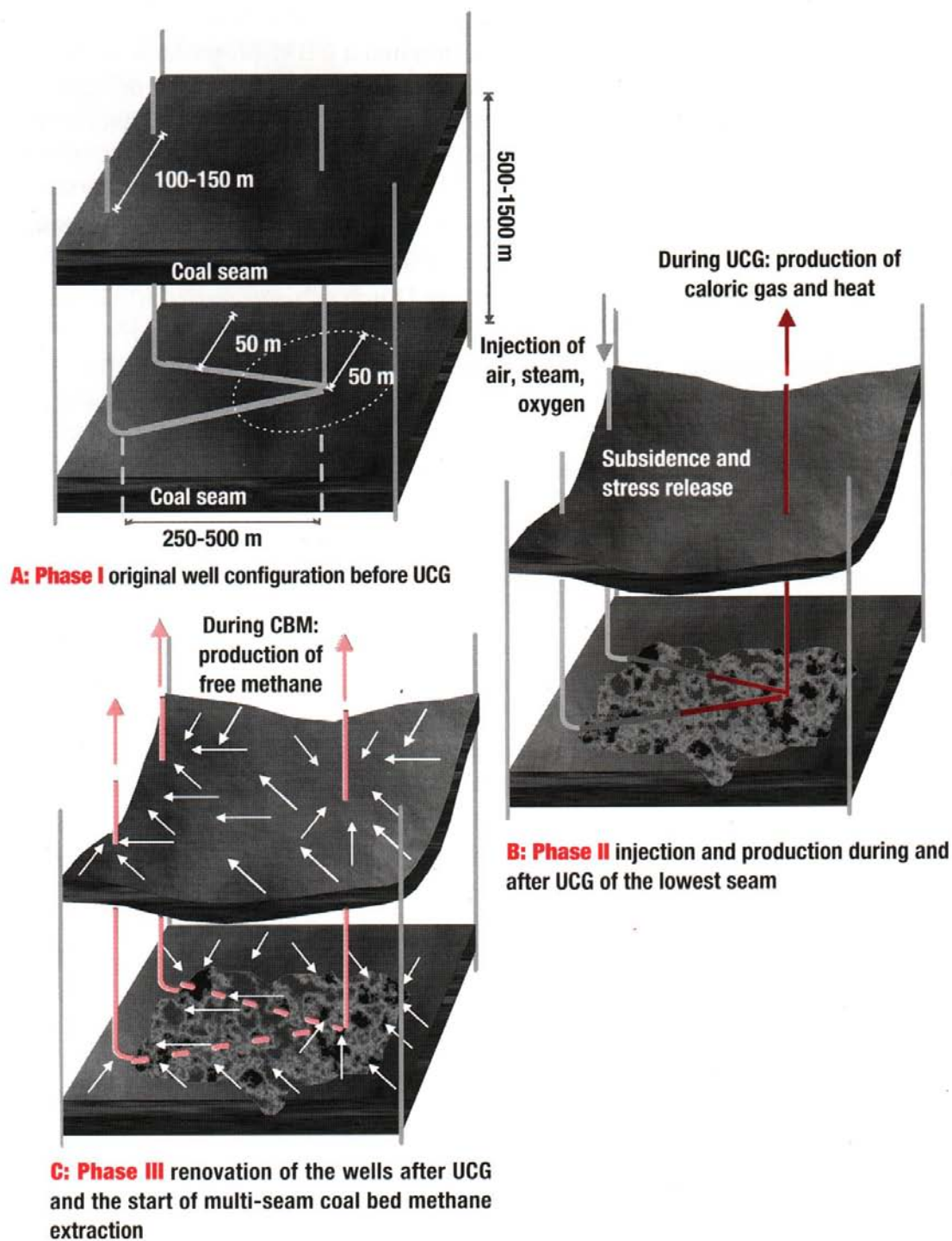
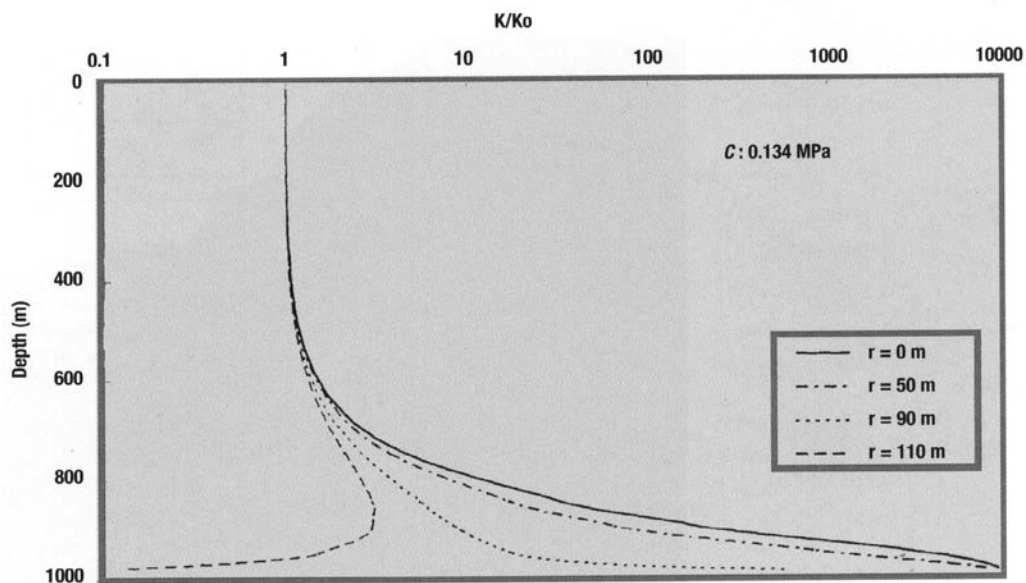


Figure 6.1 - Phases Involved in Enhancing Coal Bed Methane Recovery from UCG



K = disturbed permeability
 K_0 = undisturbed permeability
 r = radius from centre of ucg cavity

Figure 6.2 - Simulation of the Change in Coal Permeability Induced by the Stress Relief Associated with UCG

6.5 CONSEQUENCE OF LEAKAGE

Any leakage in the short term would devalue the benefits of underground CO₂ storage. The EU NASCENT project, led by the British Geological Survey (BGS), is studying several natural CO₂ accumulations and seeps in Europe to determine the long term storage integrity of such reservoirs.

If CO₂ rises above the depth at which it can exist in its supercritical state it will expand rapidly. If there are no overlying cap rocks, it will continue to migrate upwards and may be accompanied by dissolution in shallow aquifer waters, potentially increasing the pH, before reaching surface.

Slow seepage to surface would have only localised effects on ecosystems, whereas high flux or episodic releases may carry more risk. Effects may be intensified in confined or sheltered areas.

A sudden release of a large quantity of CO₂ could pose a serious local threat to humans and ecosystems. A CO₂ concentration in atmosphere of 30% is the fatal threshold, and there have been incidents where degassing from natural reservoirs has resulted in fatalities.

The most likely path for leakage from artificial storage is through man-made pathways such as well bores which penetrate the reservoir formation cap rock. Such risks can be minimised by proper design of the well injection and

avoiding over-pressurising the reservoir. Injection via a deviated horizontal well will avoid puncturing the cap rock above the injection point thus increasing security.

Monitoring technologies to provide early warning of sub-surface CO₂ seepage are being developed in CO₂ storage projects.

Compared to natural gas storage, the risks of CO₂ storage are likely to be less, due to the fact that CO₂ is not flammable or explosive and readily disperses in moving air. Risks more pertinent to CO₂ are its ability to dissolve in water, and consequent impact on pH, its corrosive effect on certain materials and, due to its density being greater than that of air, the risk of accumulation in topographic depressions where there is limited air flow.

7. UK ENVIRONMENTAL REGULATORY REGIME FOR UCG

Although there is no experience of environmental regulation of UCG operations in the UK, there is some experience in Europe. The most recent trial in Europe was the joint European trial that took place at El Tremedal in Spain, where the gasification phase occurred in 1997. This trial was classified as a mining project, however the relevant authorities did not require an EIA to be undertaken. An activity licence for the trial was obtained from the local Council, and as part of that process an atmospheric dispersion modelling study was undertaken to predict the effects arising from combustion of the product gases. The only other major area of environmental regulation related to the product water, which was designated as a toxic residue and required a special permit for disposal.

As part of the consideration of the UK environmental regulatory regime that would apply to UCG, a Consultation Paper entitled 'Review of the Environmental and Planning Issues of Underground Coal Gasification' (Appendix G) was produced. The Consultation Paper, which invited views on the environmental and planning issues surrounding the UCG programme and, in particular, on the likely planning and environmental legislation to which the trial and semi-commercial operation would be subject, was sent to the following organisations:

- DTI, Oil and Gas Division;
- Coal Authority;
- Environment Agency;
- Scottish Environmental Protection Agency;
- Northern Ireland Environment and Heritage Service;
- Health and Safety Executive;
- Office of the Deputy Prime Minister, Minerals Planning Division;
- Scottish Executive;

- National Assembly for Wales;
- Northern Ireland Department for the Environment;
- Planning Officers Society;
- Planning Officers Society (Wales);
- Scottish Society of Directors of Planning;
- Royal Town Planning Institute; and
- Scottish Enterprise Energy Group.

The purpose of the consultation was to gain the views and opinions of those organisations likely to be involved in the regulation of the environmental and planning aspects of the UK's proposed UCG development programme. A collation of the responses that were received is provided in Appendix H.

This section provides an overview of current understanding of the UK environmental regulatory regime that would apply to UCG and the associated implications, taking into account the responses that were obtained to the Consultation Paper. It should be noted that, in addition to the legislation discussed below, the normal Health and Safety requirements that would apply to any industrial operation would apply to the trial and semi-commercial operation.

7.1 PLANNING REGULATION AND ENVIRONMENTAL ASSESSMENT

The purpose of this section is to identify UK planning legislation applicable to both the trial and semi-commercial UCG operations and to identify the issues that would need to be considered in presenting the process for approval to the relevant authorities. The section is generic in that legislation and guidance unique to specific sites are not considered. The main body of the section focuses on the planning framework in England. Important differences between the English legislative framework and those of Wales and Scotland are provided at the end of the section. Northern Ireland does not have suitable coal reserves for UCG.

There is no specific provision for the UCG process within the UK statutory planning framework. However, due to the numerous elements of UCG there are a number of similar processes identified in planning legislation and guidance which share the same characteristics as UCG.

7.1.1 Legislative Approvals

The main primary legislation relevant to the planning consents required for a UCG trial and semi-commercial operation is:

- Town and Country Planning Act 1990.

The framework for the trial could also include the following primary legislation:

- Pipelines Act 1962.

The framework for the semi-commercial operation could also include the following primary legislation:

- Electricity Act 1989;
- Pipelines Act 1962; and
- Planning (Hazardous Substances) Act 1990.

In addition, there are various Regulations which are also of relevance. These would include:

- Town and Country Planning (Environmental Impact Assessment) Regulations 1999;
- Town and Country Planning (Minerals) Regulations 1995;
- Conservation (Natural Habitats & Conservation) Regulations 1994;
- Protection of Badgers Act 1991; and
- Schedule 14, Environment Act 1995.

Determining Authority

The UCG trial would not include electricity generation. Development of a trial site would need to be the subject of a planning application submitted in accordance with the Town and Country Planning Act 1990. In planning terms the trial is likely to be considered to be a mining operation, with the surface elements ancillary to that. The appropriate planning authority for a mining operation is the mineral planning authority. The mineral planning authority is:

- the County Planning Authority in respect of a site in a non-metropolitan County; or
- the Local Planning Authority in respect of a site in a metropolitan district or London Borough or unitary district; or
- the National Park Authority.

As part of the semi-commercial operation, it will be necessary to construct a power plant in order to demonstrate the viability of UCG. The semi-commercial operation involving electricity generation facilities and processing of fuel for generation is likely to raise wider planning considerations. Applications to develop a power plant with a capacity of less than 50 MWe can be submitted to the relevant planning authority under the Town and Country Planning Act 1990. It is possible however that the semi-commercial plant may have an electrical output of greater than 50 MWe, in which case an application must be submitted to the Secretary of State for Trade and Industry under Section 36 (S.36) of the Electricity Act 1989.

The generation of electricity using the product gas in the semi-commercial operation would be considered to be an industrial process in planning terms. The gasification phase would however continue to be classed as a mining operation, however this could not be considered to be ancillary to the industrial operation. As a consequence, for the semi-commercial operation, should the capacity of the electricity plant exceed the 50 MWe threshold, it will be necessary to obtain consent under the Electricity Act 1989 and submit a

separate application to the mineral planning authority for the mining operation. The application under the Electricity Act 1989 would be determined by the Secretary of State for Trade and Industry, and not the Local or County Planning Authority. However, as part of this application process it would be necessary to consult with several functions of the Local and County Authorities including planning, mineral planning, environmental health and highways. It should be noted that if the power plant did not exceed the 50 MWe threshold, then a planning application would be made to cover the two operations (mining and industrial). This would be determined by the Local Authority.

Transmission Lines

Transmission lines may be necessary for the semi-commercial operation. Permission for this can be obtained by making an application under S.37 of the Electricity Act 1989 to the Secretary of State for Trade and Industry. It is normal practice for the National Grid to obtain this consent on behalf of the developer. The submission of an EIA for all S.37 transmission lines is mandatory under the Electricity Works (Environmental Impact Assessment) Regulations 2000. An assessment of the visual impact of transmission lines and the unsubstantiated threat from electromagnetic radiation would be critical to a S.37 application.

Pipeline

Under the Pipelines Act 1962 a Pipeline Construction Authorisation (PCA) is required to construct an underground pipeline for the supply of gas to a site. An application for planning permission to construct the pipeline would also be required and 'no valid objection' status is required before a PCA is given by the DTI. If gasification agents were delivered to the UCG trial site by road a PCA would only be required for the importation of natural gas. It is therefore anticipated that a PCA could be required for both the trial and the semi-commercial operation.

Hazardous Substances Consent

Under the Planning (Hazardous Substances) Act 1990 a hazardous substances consent is required for the presence of a hazardous substance in an amount at or above its controlled quantity. It is likely that quantities of hazardous substances present for the semi-commercial operation would be above the levels in Schedule 1 of the Planning (Hazardous Substances) Regulations 1992 as amended by the Planning (Control of Major Accident Hazards) Regulations 1999. A hazardous substances consent would therefore be required for the semi-commercial UCG operation.

The hazardous substances authority (the mineral planning authority) is required to consider whether the proposed storage or use of a significant quantity of a hazardous substance is appropriate in a particular location, having regard to the risks associated with the persons in the surrounding area and the wider implications for the community.

Applicants should submit a prescribed form and must publicise the application. The hazardous substances consent application should run concurrently with the planning application as they are inter-dependent. The authority is required to consult with the Health and Safety Executive and the Environment Agency. Where consent is granted, the authority must set up a consultation zone within which proposals for future development are referred to the consultees to consider public safety.

7.1.2 Planning Policy

In accordance with Section 90 of the Town and Country Planning Act 1990, in granting authorisation under S.36 and S.37 of the Electricity Act 1989, and the Pipelines Act 1962, the DTI may direct that planning permission for this development shall be deemed to be granted. That would mean that successful applications on these fronts would result in a deemed planning consent for the power plant, the overhead transmission lines and the underground pipeline. However it is important to note that any objections of the planning authority to such applications may result in a public inquiry and that a direction from the DTI may subject the authorisation to conditions. It will therefore be necessary to consider the planning policy context and planning history for each site proposed for a trial or semi-commercial operation. The mining aspect of the trial would still need to be authorised by the mineral planning authority.

With regard to planning policy it must be noted that presently there does not exist any Government guidance on the specific process of UCG. However, as regards the drilling of both exploration and production wells, the emerging policies in the draft Planning Guidance Note on On-shore Oil, Gas and Coalbed Methane Development, published by the Department of the Environment, Transport and the Regions in October 1999, is a clear guide to the likely planning considerations to be attached to this element of a UCG trial. The document is already accorded some weight in the planning process. It is to be revived in the coming months by the Office of the Deputy Prime Minister as part of the programme of planning reform, and is likely to be extended to cover the drilling and associated surface development element of UCG.

Mineral Planning Guidance

Mineral Planning Guidance Notes (MPGs) provide advice for both the minerals industry and mineral planning authorities. The MPGs, particularly MPG 1: General Considerations and the Development Plan System and MPG 2: Applications, Permissions and Conditions, provide general guidance on mineral development which should be considered in the development of a UCG trial site and a semi-commercial UCG operation.

The draft Planning Guidance Note on On-shore Oil, Gas and Coalbed Methane Development referred to above provides a policy framework to ensure that the

development of onshore gas resources is carried out with the least environmental impact. There is particular emphasis on the need for pre-application discussions with the planning authority, community liaison and proper site restoration and aftercare. It is established Government policy that restoration and aftercare will be required to make mineral workings fit for beneficial after-use and to preserve or enhance the overall quality of the environment. Sustainable development requires that wherever practicable land should be restored to its original quality. Restoration schemes should take into account and, where possible, provide positive benefits for both wildlife and geological conservation. These considerations can be expected to be applied to the assessment by the planning system of UCG proposals.

Minerals Policy Statement (MPS) 2: Controlling and Mitigating the Environmental Effects of Mineral Working is an important emerging policy document which seeks to bring together advice contained within a number of MPGs and good practice guides. The Office of the Deputy Prime Minister looks to all planning authorities and to mineral operators to follow the policies it sets out to ensure that environmental impacts of mineral workings are minimised and controlled. The draft of this statement (issued for consultation in February 2003) sets out policy on the planning considerations for the formulation of development plans and for decisions on individual planning applications. MPS 2 places emphasis on the importance of an Environmental Management System (EMS), an important component of which is a commitment to maintaining community relations. The statement contains advice on preparing an EMS and more specifically provides guidance on how to assess and mitigate dust and noise impacts from mineral workings. Later annexes are planned, to deal with traffic, blasting and water and landscape impacts.

Planning Policy Guidance

Relevant Government guidance on planning policy will depend on site circumstances. The following Planning Policy Guidance Notes (PPGs) would be particularly relevant to UCG:

- PPG 2: Green Belts;
- PPG 7: The Countryside: Environmental Quality and Economic and Social Development;
- PPG 23: Planning and Pollution Control; and
- PPG 24: Planning and Noise.

PPG 2 is particularly pertinent owing to the special status afforded to some mineral proposals in the Green Belt and is considered in more detail here.

PPG 2 states "Minerals can be worked only where they are found. Their extraction is a temporary activity. Mineral extraction need not be inappropriate development: it need not conflict with the purposes of including

land in Green Belts, provided that high environmental standards are maintained and that the site is well restored.”

The location and life of a UCG trial or semi-commercial operation is limited by the presence and extent of appropriate deposits. The drilling and gasification parts of the process are therefore considered to constitute a mining operation. Whether these elements of the development are inappropriate development will depend upon site circumstances as this will determine whether the development of the site maintains the openness of the Green Belt and does not conflict with the purposes of including land in the Green Belt.

The above ground use of the product gas to generate electricity would be an industrial use which, although connected to the gasification, may be perceived to be an industrial use which is inappropriate development in the Green Belt. The construction of power generation plant (and potentially the gasification of the coal depending on local conditions) is inappropriate development and exceptional circumstances would need to be demonstrated to justify a departure from Green Belt policy.

UCG would be considered to be inappropriate development if it does not maintain the openness of the Green Belt and conflicts with the purposes of including land in the Green Belt.

The regional planning framework would be set out in Regional Planning Guidance, and in the Regional Spatial Strategies (RSS) that are to replace it under the Planning and Compulsory Purchase Bill.

Development Plan

Local Authorities prepare development plans to guide development in their areas. UCG proposals would therefore be judged against the policies within the development plan. The statutory development plans relevant to UCG include the local plan, structure plan (unitary development plan in metropolitan areas) and the minerals local plan. Under S.54a of the Town and Country Planning Act 1990, in determining a planning application, the planning authority must have regard to the development plan and the determination shall be made in accordance with the plan unless material considerations indicate otherwise.

The Planning and Compulsory Purchase Bill proposes to replace local plans and structure plans in England with statutory RSS, to be prepared by the Regional Assemblies (whether or not elected) and by Local Development Frameworks (LDFs). The minerals local plan will be replaced by a Minerals and Waste Development Scheme which will set out the Local Development Documents (LDDs) which a planning authority propose to produce on minerals and waste matters. The exact details will vary depending on whether the area concerned is a shire county (whose statutory planning responsibilities will in future be limited to minerals and waste matters) or

district/unitary authorities handling the full range of development. There will be transitional arrangements for movement from existing plans to the new frameworks to avoid the loss of up to date plans and policies. Policies within the emerging LDF and LDD will be material considerations in the determination of planning applications. Planning authorities will have to have regard to the policies of their Regional Assembly in their RSS, and if relevant the RSS of neighbouring regions, in drawing up their LDF and LDD.

The Office of the Deputy Prime Minister expects Mineral Planning Authorities to have made a significant level of progress on LDD within the next few years. These are likely to consider UCG. If however this is not the case, then it will be very unlikely that many, if any, mineral planning authorities located in the areas on the deep coalfield at which any UCG proposals would be aimed would have adopted policies for development involving UCG, given the absence so far of such development in England, or any complete planning guidance. A few authorities in coal bed areas may have embryonic policies for CBM developments, and certain limited areas of the country may have responded to past experience and the existence of local resources by drawing up policies for onshore oil and gas exploration and extraction. If there are no directly applicable planning policies available this would lead to the situation where the First Secretary of State might call in the planning application as a novel application. Also, if recommended for approval by the Local Planning Authority, such an application would be referred to the First Secretary of State as a departure from the development plan.

Planning Need

Owing to the scale of both a trial and a semi-commercial operation the justification to carry out either forms of development would need to be fully documented in any application. If necessary, the material circumstances which justify a departure from development plan policy would need to be clearly documented, ie it must be demonstrated that the potential adverse impacts of UCG would be outweighed by the benefits. The benefits and adverse impacts would be many and would include the following:

- the need to explore the potential of cleaner coal technologies;
- the need to address the geological and technical challenges specific to coal seams in the UK;
- the economic potential of exploiting deeper coal reserves;
- the environmental benefit of UCG as opposed to conventional coal fired power generation eg potential capturing and recycling of CO₂, no waste tips, no ash handling, reduced transport requirements through electricity generation at the location of fuel source; and
- the potential impact on the environment.

7.1.3 EIA Requirements

Owing to the numerous components of UCG the appropriate EIA Regulations and application of them is open to some interpretation.

The European Council Directive on Environmental Assessment (85/337/EEC) as amended by EC Directive (97/11/EC) was enacted by a number of regulations including:

- Town and Country Planning (Environmental Impact Assessment) Regulations 1999 (from here on referred to as the Planning EIA Regulations);
- The Electricity Works (Environmental Impact Assessment) Regulations (England and Wales) Regulations 2000 (S.I. 1927) (from here on referred to as the Electricity EIA Regulations); and
- The Pipe-line Works (Environmental Impact Assessment) Regulations 2000 (from here on referred to as the Pipeline EIA Regulations).

Where appropriate it will also be necessary to have regard to the requirements of the Conservation (Natural Habitats & Conservation) Regulations 1994.

Planning EIA Regulations

Under the Planning EIA Regulations “Extraction of petroleum and natural gas for commercial purposes where the amount exceeds 500 tonnes per day in the case of petroleum and 500,000 cubic metres in the case of gas” is classed as Schedule 1 Development. This means that an EIA for such a development is mandatory.

Under the Planning EIA Regulations certain forms of development above specified thresholds within Schedule 2 require an EIA subject to selection criteria in Schedule 3. The following is classed as ‘Schedule 2 Development’:

- oil and gas pipeline installations where the area of works exceeds 1 hectare;
- industrial installations for the production of electricity, steam and hot water where the area of the development exceeds 0.5 hectares;
- underground mining;
- deep drilling where the area of the works exceeds 1 hectare; and
- geothermal drilling within 100 metres of any controlled waters.

The above developments may require an EIA depending on the characteristics of the development, the location of the development and the characteristics of the potential impact. The applicant can request a screening opinion from the determining authority to establish whether the development requires an EIA.

Electricity EIA Regulations

The Electricity EIA Regulations apply to applications made under S.36 and S.37 of the Electricity Act 1989 for consent to construct generating stations and to install electricity lines above ground.

For development defined within Schedule 1 of the Electricity EIA Regulations, an EIA is mandatory. Non-nuclear power stations with a heat output of 300 MW or more require an EIA. Similarly an electricity line above ground with a voltage of 220 kV or more and a length of more than 15 km requires an EIA. The development of generating stations for which S.36 consent is required, is classed as a Schedule 2 development under the Electricity EIA Regulations. An electricity line installed above ground with a voltage of 132 kV or more, the installation of which will require a S.37 consent, is also Schedule 2 Development.

Pipeline EIA Regulations

Pipelines for the transport of gas, oil or chemicals with a diameter of more than 800 mm and a length of more than 40 km require a PCA under S.1 of the Pipelines Act 1962. This would not apply to the internal transmission pipelines but may apply to any supply of natural gas to the combustion unit/power plant at the UCG site. An EIA is mandatory for these pipelines, as it is in the situation where the Secretary of State for Trade and Industry does not give direction that the scheme will not have a significant effect on the environment.

Interpretation

Based on research undertaken with respect to the scale and nature of the proposed development it is concluded that an EIA is not mandatory for a trial or a semi-commercial operation under the Planning EIA Regulations. However given the scale of both of these operations it is considered that the development would be defined as a Schedule 2 development under all of the EIA regulations. Given the characteristics of UCG and its potential impact it is highly probable that a formal EIA would be required for both a trial and a semi-commercial operation. This could be confirmed by obtaining a screening opinion from the determining authority.

Once it has been confirmed that an EIA is required, it would be advisable to seek a formal scoping opinion from consultation bodies to define the key issues to be considered in the Environmental Statement. The consultation bodies for a scheme submitted under any of the EIA Regulations include:

- the relevant planning authority;
- the Countryside Agency;
- English Nature; and
- the Environment Agency (not mandatory for a S.37 consent).

Under the Planning EIA Regulations it would be necessary to consult with any body that the relevant planning authority is required to consult as specified in article 10 of the Town and Country Planning (General Development Procedure) Order 1995. The additional consultees from which a scoping opinion should be sought will depend on site context but could include:

- the local Highway Authority;
- English Heritage;
- Department for Environment, Food and Rural Affairs; and
- the Health and Safety Executive.

For a S.36 or S.37 application it is not a statutory requirement to seek an EIA scoping opinion from the additional consultees specified in article 10 of the aforementioned Order. However in practice this may be necessary.

Further details about the potential content of an Environmental Statement are provided in the following section.

With 'EIA Development' the local planning authority has 16 weeks rather than eight weeks to determine the application. The applicant has a right of appeal if the application is not determined within the 16 week period.

7.1.4 Potential Content of an Environmental Statement

This section provides information on the potential content of an Environmental Statement produced under the Planning EIA Regulations for both the trial and semi-commercial operation, excluding consideration of the power plant.

An Environmental Statement would need to include the following:

- a site and project description;
- a baseline study, including data on existing environmental conditions collated from local authorities, statutory bodies, other documentary sources and field studies;
- an assessment of the construction and operational effects on the environment; and
- identification of potential mitigation measures to reduce the severity of the effects.

Environmental effects relating to the following areas would be assessed for inclusion in the Environmental Statement:

- planning context, including consideration of the planning history of the site;
- air quality, including consideration of gaseous emissions and dust;
- water quality, including surface water and groundwater issues, with the former including consideration of wastewater treatment and disposal, and the latter including consideration of gas generation issues and groundwater risk evaluation;
- land quality, including consideration of subsidence issues;
- solid residues, including consideration of proposed disposal routes for all solid residues;

- ecology, including effects of the site footprint, emissions to air and to water and the proposed disposal of solid residues;
- transport, including consideration of the effects of road traffic on the local road network;
- noise, with particular emphasis on drilling noise;
- landscape and visual amenity, with particular emphasis on sensitivity issues relating to developments in rural landscapes;
- cultural heritage, including consideration of effects on local archaeology;
- socio-economic issues; and
- health and safety issues.

The above listed individual assessments would be amalgamated to produce the Environmental Statement, which would include a non technical summary and would also provide a demonstration of why potential alternative sites/routes have been discounted in order to establish that the proposed development represents the Best Practicable Environmental Option. In the case of UCG, the correct geological and hydrogeological conditions are of paramount importance and it is on this basis that a search for a UCG site commences. It is after this point that the other site selection criteria are applied both to rank search areas and to determine the most appropriate sites within search areas.

7.1.5 Other UK Legislation and Policy

The above discussion generally applies to Wales and Scotland, as well as England. However critical legislation, organisations and policy guidance specific to Wales and Scotland are set out below.

Wales

In Wales the consultation bodies with respect to the EIA scoping process are different; they are as follows:

- the relevant local authority;
- Environment Agency Wales;
- Countryside Council for Wales; and
- Welsh Assembly Government.

MPG2 applies to England only; the equivalent guidance in Wales is Mineral Planning Policy Wales (2000).

Scotland

The legislation that applies in Scotland is as follows:

- Town and Country Planning (Scotland) Act 1997;
- Planning (Hazardous Substances) (Scotland) Act 1997;

- Town and Country Planning (Minerals) (Scotland) Regulations 1998, [SI 1998 No 2913];
- The Planning (Control of Major Accident Hazards) (Scotland) Regulations 2000 [SI No 179];
- The Environment Impact Assessment (Scotland) Regulations 1999;
- The Electricity Works (Assessment of Environmental Effects) (Scotland) Regulations 2000 [SSI 2000 No 320]; and
- The Pipe-line Works (Environmental Impact Assessment) Regulations 2000 [SI 2000 No 1928].

Scottish Planning Policies (SPPs) provide statements of Scottish Executive policy on nationally important land use and other planning matters, supported where appropriate by a locational framework. These are gradually replacing the earlier series of National Planning Policy Guidelines (NPPGs) which were introduced in 1993. The relevant policy guidance is provided by:

- SPP1: The Planning System;
- SPP 2: Economic Development;
- NPPG 4: Land for Mineral Working;
- NPPG 5: Archaeology and Planning;
- NPPG 10: Planning and Waste Management;
- NPPG 14: Natural Heritage;
- NPPG 15: Rural Development;
- NPPG 16: Opencast Coal and Related Minerals; and
- NPPG 18: Planning and the Historic Environment.

In addition, the Scottish Executive publish Planning Advice Notes (PANs) which provide advice on good practice and other relevant information. Circulars also provide statements of Scottish Executive policy and guidance on policy implementation through legislative or procedural change. PANs/Circulars which may be particularly relevant to UCG are:

- PAN 50: Controlling the Environmental Effects of Surface Mineral Workings;
Annex A: Noise;
Annex B: Dust;
Annex C: Traffic;
Annex D: Blasting;
- PAN 51: Planning and Environmental Protection;
- PAN 56: Planning and Noise;
- PAN 58: Environmental Impact Assessment;
- PAN 60: Planning for Natural Heritage;
- PAN 64: Reclamation of Surface Mineral Workings;
- SDD Circular 24/1985: Development in the Countryside and Green Belt;
- SDD Circular 12/1986: Planning Control over Onshore Oil and Gas Operations; and

- SDD Circular 10/1999: Planning and Noise.

The arrangements for the delivery of strategic planning in Scotland are currently under review. The review of the NPPG series is well underway with the publication of SPP1: The Planning System, SPP2: Economic Development and SPP3: Planning for Housing. Work is progressing on the National Planning Framework with further stakeholder consultation followed by publication towards the end of 2003.

The arrangements for strategic planning are being revised with the replacement of structure plans with City Region Plans covering the four main cities. At the local level, pilot projects with two local authorities are helping to identify the barriers and opportunities to better local plans. Consultation on the new arrangements for development planning will be carried out later in 2003. Whilst primary legislation will be required for the new strategic arrangements, much can be achieved through secondary legislation, policy and advice.

The determination of cases submitted under S.36 and 37 of the Electricity Act 1989 has been administratively devolved to Scottish Ministers and are processed by the Scottish Executive. All local Authorities in Scotland (32) are unitary planning authorities and are responsible for cases submitted under the Town and Country Planning (Scotland) Act 1997.

The following organisations would need to be consulted in Scotland:

- the relevant local authority;
- Scottish Environmental Protection Agency;
- Scottish Natural Heritage; and
- Historic Scotland.

7.2 INTEGRATED POLLUTION PREVENTION AND CONTROL

Following receipt of responses to the Consultation Paper (Appendix H), a confirmatory meeting was held with the Environment Agency Power Generation Policy Advisor specifically to consider issues relating to IPPC. The outcome of this meeting has been taken into account in producing this section.

The UCG process, for both the trial and semi-commercial operation, would fall under the Pollution Prevention and Control (England and Wales) Regulations 2000 (PPC Regulations 2000) as a part A(1) installation and the Pollution Prevention and Control (Scotland) Regulations 2000 (PPC(Scotland) Regulations) as a Part A installation. Therefore operation of the process would be conditional upon obtaining an IPPC permit from the Environment Agency in England and Wales, and from the Scottish Environmental Protection Agency in Scotland.

The IPPC permitting process addresses the following considerations:

- management systems/techniques;
- materials input (raw materials, water) including:
 - selection;
 - minimisation of use, and
 - minimisations of impacts;
- waste management and minimisation;
- details of activities and abatement techniques;
- emissions (to air, surface water, sewer, groundwater and land) and their environmental impacts;
- environmental accidents;
- energy efficiency;
- odour;
- heat, noise and vibration;
- monitoring programme(s); and
- decommissioning (site report and site closure plan).

The EU IPPC Directive contains a research and development (R&D) exemption clause that was not fully implemented in Great Britain. Consultation on the R&D exemption is currently being undertaken across Europe. If the PPC Regulations 2000 and the PPC Regulations (Scotland) 2000 were to be modified to implement the R&D exemption, then the trial might be exempt from the full requirements of IPPC.

For the trial, it is suggested that the gasification process is most likely to be covered by the following section of Schedule 1 of the PPC Regulations 2000 and PPC (Scotland) Regulations 2000:

- Section 1.2 Gasification, Liquefaction and Refining Activities Part A(1) (d), Coal or lignite gasification.

For the semi-commercial process, it is suggested that the gasification process is most likely to be covered by the above section of Schedule 1 whilst the purification stages and the associated surface gas utilisation activities might be covered by the following sections respectively:

- Section 1.2 Gasification, Liquefaction and Refining Activities Part A(1) (f), Purifying and refining any product of any of the activities falling within paragraphs (a) to (e) or converting it into a different product; and
- Section 1.1 Combustion Activities Part A(1) (a) Burning any fuel in an appliance with a rated thermal input of 50 megawatts or more.

IPPC requires the application and use of BAT. The IPPC permit would include emission limits derived from ELVs/achievable releases, based on BAT, for emissions to air and water. Sectoral technical guidance will contain

information on what is considered to be BAT for the sector and the corresponding achievable releases for IPPC installations. The sectoral technical guidance is written by the Regulatory Authorities on the basis of the contents of the EU BAT Reference Documents (BREFs).

Sectoral technical guidance for gasification, liquefaction and refining activities, and combustion activities is not yet available, although guidance notes from the previous regulatory regime (Integrated Pollution Control) are available, as is the first draft of the combustion BREF. However currently there is no knowledge concerning the extent to which the BREF will address the combustion of fuels such as the product gas of UCG, as opposed to more common fuels. Also it is considered that none of the existing or planned guidance is relevant, in whole, to the UCG trial or semi-commercial process. Hence information concerning BAT for the sectors and achievable releases is currently uncertain.

For the trial, it is anticipated that the product gas would not need to be treated prior to its combustion in a combustion unit (or emergency flare), which might be co-fired with natural gas. As concerns ELVs/achievable releases that might apply, it may well be up to the operator to make proposals. These would have to take into account the fact that the Regulatory Authorities would expect to see no risk to environmental quality and should be in line with ELVs/achievable releases for comparable plant where they exist (for example if a combustor unit with no cooling were to be employed then the dioxin emission limit should not be any greater than that for an incinerator). A robust site specific BAT argument would need to be produced for the whole installation.

For the semi-commercial process, the ELVs/achievable releases specified in the planned technical guidance for gasification, liquefaction and refining activities may apply. The ELVs/achievable releases for aqueous emissions are likely to be those that are attainable by wastewater treatment plants (Section 5). In addition, the other ELVs/achievable releases that apply would be in line with the guidance note for the particular combustion plant that is selected for use, which would be designed to allow co-firing with natural gas when necessary. For example if gas turbines were to be used then the emissions to air that are determined by the combustion plant would be expected to be in line with the ELVs/achievable releases in the guidance note addressing Integrated Gasification Combined Cycle (IGCC). Site specific BAT may then need to be determined for the whole installation.

As concerns the extent of the installation for the IPPC permit, for the trial it is considered that all of the plant would be included. For the semi-commercial operation it may be different if the CO₂ is removed from the product gas, depending on whether the CO₂ is pumped elsewhere for use or is used on site. In the former situation, the installation may exclude the use of the CO₂, whilst in the latter situation it is more likely to be included.

In cases where new processes are being considered for potential permitting, the normal procedure within the Environment Agency is for the relevant Policy Advisor to present a short paper to the Environment Agency's IPPC Interpretation Group. This paper provides a brief outline of the process and the specific questions that are being asked. The Interpretation Group would then provide answers to these questions. Such an approach in relation to the trial and semi-commercial UCG operation would obviously provide some further information in relation to permitting under the IPPC regime, but the only certain way to obtain complete clarification would be to submit an IPPC application.

More information relating to emissions to groundwater and surface water for the UCG trial and semi-commercial operation is included in the following section.

7.3 SURFACE AND GROUNDWATER QUALITY

Benzene, phenols, ammonia (and nitrate), boron and some of the other minor contaminants that are released from the gasification process via gas escapes or leaching are found in the IPPC List II of families and groups of substances (EC Directive C76/3-018). Therefore these substances present a potential impact to the groundwater environment. Some of the trace inorganics that have been recorded within UCG reactors (such as heavy metals) are also classed as List I or II substances.

As part of this project, the Groundwater Policy Unit of the Environment Agency was consulted about groundwater quality legislation and authorising of UCG. An initial response, which is presented below, was provided by the Groundwater Policy Unit, concentrating on the high level policy response and requirements for the authorisation of a trial or semi-commercial site.

In terms of policy response, the Environment Agency's primary concern is that the UCG process generates List I and II substances, as defined by the Groundwater Directive, and these will almost certainly enter 'groundwater' in the immediate vicinity of the reactor. However, the Environment Agency realises that deep operations such as this do not necessarily represent a risk to the shallower aquifers that constitute water resources, as long as suitable site selection, technical analysis and mitigation measures are carried out. The Environment Agency suggested that there are two possible options for authorising UCG operations within the legal requirements of the Groundwater Directive:

- the emissions could be considered as 'indirect discharge' of List II substances that originated as a by product from the process of 'disposal' of substances from the cavity, rather than a specific intended discharge (unintentional leakage from underground fuel storage is an

- example of this type of regulation). Section 19 of the Regulations allows the issuing of prohibition notices that place controls on such activities, which cannot otherwise be authorised. However, it was considered that this approach would be hard to justify as there is no specific attempt to dispose of the UCG emissions that escape underground other than to the surrounding underground strata; and
- the Groundwater Directive allows exemptions for the discharge of List I and II substances provided that “investigation reveals that the groundwater is permanently unsuitable for other uses, presence of that substance does not impede exploitation of ground resources and conditions are imposed which require that all technical precautions are observed to prevent the substance from reaching other aquatic systems or harming other ecosystems”. Authorisation based on this route has been accomplished once previously in England, at a hazardous waste disposal site in the Anglian Region. The Environment Agency considers that this is the most likely potential authorisation route.

The site investigation/appraisal would have to gain sufficient hydrogeological data to be able to agree the extent and nature of the block of strata that contained the PU groundwater at a given site. The Environment Agency indicated that pre-defined parameters were not appropriate in England and that any agreed zone would be based on site specific technical factors, generally aimed at ensuring the PU zone was almost certainly hydrogeologically isolated from significant aquifers in the overburden. The definition of this PU zone is a key parameter in the site investigation and risk assessment.

Investigations at the site would have to provide suitable proof that contaminants from the process would not escape from the defined PU zone. The definition of ‘suitable proof’ will be site specific, but a robust risk based approach that could prove a negligible risk of escape from the zone would usually be acceptable to the Environment Agency. As ammonia and nitrates are List II substances and ammonia is contained within the gaseous emissions from UCG, the risk assessment would have to prove a negligible risk of gas escape from the PU zone.

Re-circulation of process waters into the cavity should not present a legal problem once the PU zone had been determined, as long as they remained within this zone. Injecting process waters back into the cavity would probably not require a discharge consent beyond the main Groundwater Regulations authorisation for the site. However, this would be site specific and there may be consent requirements if the Environment Agency felt that extra control was needed. Authorisation based on exemption means that there would be no specific additional legislative requirements for venting, flushing and post operation cavity washing operations that could be used for UCG, apart from possibly requiring a groundwater abstraction license, as discussed later.

The consultation with the Groundwater Policy Unit also included a brief review of the implications of the Water Framework Directive (WFD) and the revised Groundwater Directive. Although uncertainties remain about the legislative changes, the general conclusion was that legislation is very unlikely to become less strict than the current regulations. Potential key changes were identified as follows:

- the definition of contaminants will change around 2015 under the WFD as List I and II will be replaced with a broader definition of 'pollutants', with a ban on direct injection of pollutants to groundwater. These are likely to split into 'hazardous' and 'priority hazardous' materials, with a ban on 'discharge to the environment' for 'priority' materials, ie not just to groundwater. There is currently no list of 'priority' substances; and
- the WFD specifically refers to the non-introduction of non-potable groundwaters into potable horizons.

The WFD limits the definition of activities that can be exempt by the PU groundwater clause. Fortunately for UCG development there is particular reference to the extraction of hydrocarbons.

As the process would require authorisation from the Environment Agency under the Groundwater Regulations, operational and post operational monitoring would have to conform to Section 8 of the Groundwater Regulations in terms of providing 'requisite surveillance'. Such authorisation would be included within the IPPC permitting process. It is considered that monitoring to conform to Section 8 of the Groundwater Regulations should be geared towards checking that contaminants are not migrating from the PU zone, rather than simply measuring contaminant movement away from the cavity. The monitoring regime as installed would need to identify potential problems with contaminant movement before it escaped beyond the confines of the PU zone. Monitoring requirements are therefore very site specific and should be based on identified potential migration pathways. They are unlikely to require specific monitoring boreholes within the target coal seam, other than the injection and production wells, but again this would be site specific and dependent on the Regulator. The set up of the monitoring system will require agreement with the Environment Agency in order to gain authorisation, this would be achieved through the IPPC permitting process.

With respect to abstraction licenses, these are not required for groundwater that is 'abstracted' as part of the underground process, but the removal of any water post gasification during cavity pumping etc would probably need a license under the Water Resources Act 1991.

In terms of drilling operations, the Environment Agency would normally ask for water-based muds to be used through the main permeable aquifer horizons, but there would be fewer concerns about using oil-based muds at depth. Drilling methods should also ensure that there is no cross-

contamination of aquifer horizons, which would normally mean that upper main aquifers would have to be cased during drilling operations. For well casing and integrity, the developers would be required to prove that there was a negligible risk of escape during operations and that the wells would not provide a contaminant pathway post operations. This applies to the engineering design and mechanical integrity both during operations and after operations whilst contaminant levels in the cavity remain high.

For surface water discharges, the Surface Water (Classification) Regulations 1989, arising from EC Directive 75/440/EEC, and the Freshwater Fisheries Directive (EC 78/659/EEC) are relevant in England, the Surface Water (Fishlife) (Classification) Regulations 1997, amended 2003, are similarly relevant in Scotland. These Regulations provide the Environmental Quality Standards (EQSs) for receiving waters that are used to derive consent limits for emissions to these waters. The Scottish Executive has indicated that the Water Environment and Services Bill Act 1 has already transposed the WFD in Scotland, so the Scottish Environmental Protection Agency should be the contact for detailed implications. Under the terms of the Water Resources Act 1991 and the Land Drainage Byelaws, the prior written consent of the Environment Agency is required for any proposed works in, under or over an ordinary water course. This would apply to any discharge structure from the site. Suitable mitigation and storage measures would therefore be required on site in order to obtain the relevant discharge consent.

7.4 AIR QUALITY REGULATIONS 2000

Separate Air Quality Regulations were produced in England, Wales and Scotland in 2000. The Regulations incorporate the objectives contained in the Air Quality Strategy for England, Scotland, Wales and Northern Ireland – Working Together for Clean Air, which was published in 2000. Local authorities must review and assess the air quality in their region against these objectives. The emissions to air from the UCG trial and semi-commercial operation would require controls to ensure that they do not cause any significant contribution to the ambient air concentrations such that the objective values within the Regulations are put at risk. For both the trial and semi-commercial operation, the means of enforcing these Regulations would be via the planning and IPPC permitting regimes.

7.5 LARGE COMBUSTION PLANT DIRECTIVE

The revised Large Combustion Plant Directive (LCPD) (2001/80/EC) aims to reduce acidification, ground level ozone and particulates throughout Europe by controlling emissions of sulphur dioxide, oxides of nitrogen and dust from large combustion plants. The Directive set emission limit values for large (greater than 50 MWth) combustion plant and will be implemented in the UK through the IPPC regulatory regime. The LCPD will apply to the semi-commercial UCG operation if its rating is greater than 50 MWth. It is worth

noting that the LCPD states that compliance with the LCPD emission limit values should be regarded as necessary, but not sufficient, to ensure compliance with BAT under the IPPC regime (ie the limits set under the IPPC regime could be more stringent).

7.6 WASTE INCINERATION DIRECTIVE

The Waste Incineration Directive (2000/76/EC) covers the incineration of both hazardous and non-hazardous wastes and sets strict emission limit values for emissions to air of hydrogen chloride, hydrogen fluoride, metals, sulphur dioxides, nitrogen oxides, dioxins and furans. Discharges to water and leachate from residues are also addressed by the Directive. The Directive applies to gases derived from gasification/pyrolysis of waste. Although the UCG process involves a gas, the gas is not derived from gasification/pyrolysis of waste. Therefore the current understanding is that the Waste Incineration Directive would not apply to UCG. This understanding could be clarified by inclusion of the issue relating to the applicability of the Directive within the short paper for presentation to the Environment Agency's IPPC Interpretation Group.

7.7 GREENHOUSE GAS EMISSIONS TRADING

In April 2002, the Government introduced the UK Emissions Trading Scheme in order to encourage participants to reduce emissions of greenhouse gases. The scheme is voluntary and lasts until 2007. Exceedance of an emissions allowance will result in both a financial penalty and the allowance for the following year being reduced by the amount of the exceedance (although there will be no penalty in the initial years of the scheme). The list of 34 original participants within the scheme was greatly expanded later in 2002, when all the sectors with Climate Change Agreements became eligible for the participation in the scheme. Coal extraction is not one of these sectors.

In July 2003 the European Commission adopted a Directive on Greenhouse Gas Emissions Trading within the Community ((COM(2003) 463, 403, 364) and COM(2002) 680). The scheme will come into force in 2005 and will apply to all power plants greater than 20 MW aggregated thermal input, as well as the specified industries of refining, coke ovens, cement, steel, glass, and pulp and paper. The semi-commercial operation would fall within the remit of the Directive, and as such would be required to have a greenhouse gas permit and would be allocated a greenhouse gas allowance enabling the holder to emit a specified amount of greenhouse gasses. Allowances will be transferable. Greenhouse gas permits will include requirements for monitoring and reporting, and verification of emissions which must not exceed allowances. There will be penalties of up to £40 per tonne for non-compliance. The use of CO₂ gas separated from the UCG product gas in ECBM extraction may potentially be eligible as deductible greenhouse gas

emissions as part of a Joint Implementation project, but currently there are no established protocols in relation to these types of projects.

7.8 CONTROL OF MAJOR ACCIDENT HAZARDS

The Health and Safety Executive in conjunction with the Environment Agency administer compliance with the Control of Major Accident Hazards (COMAH) Regulations 1999. These Regulations implement the Directive on the Control of Major Accident Hazards Involving Dangerous Substances (96/82/EC). The mineral exploitation aspect of the UCG trial would be exempt from COMAH under Regulation 3, which exempts “the activities of the extractive industries concerned with exploration for, and exploitation of, minerals in mines and quarries or by means of boreholes”. This includes, for example, onshore and offshore oil and gas drilling and extraction facilities, as well as traditional mining industries. The rest of the trial would also be exempt from COMAH, providing the quantities of substances that are present on site are not greater than the qualifying quantities of substances specified in the COMAH Regulations, which is highly likely.

The mineral exploitation aspects of the semi-commercial process would also be exempt under Regulation 3. It should however be noted that this exemption does not include onshore oil and gas reception facilities. Therefore if the semi-commercial process includes gas reception facilities, and quantities of substances are present that are greater than the qualifying quantities of substances specified in the COMAH Regulations, the gas reception facilities will fall under the COMAH Regulations. If the quantities of substances that are present at the gas reception facilities are sufficient for only lower tier duties to apply, then the following requirements are relevant:

- the operator to take all measures necessary to prevent major accidents and limit their consequences to persons and the environment;
- the operator to prepare a major accident prevention policy;
- the operator to notify the Competent Authority of the required information before the start of construction of the establishment;
- the operator to provide the Competent Authority with sufficient information to demonstrate that all measures to comply with the Regulations have been taken; and
- the Competent Authority to provide information to other establishments.

If the quantities of substances that are present at the gas reception facilities are sufficient for top tier duties to apply, then the following requirements are relevant in addition to those that are listed above:

- the operator to produce a safety report;
- the operator to review and revise the safety report;
- the operator to prepare an on-site emergency plan;

- the local authority to prepare an off-site emergency plan;
- the operator/local authority to review and test the emergency plans;
- the operator/local authority to implement the emergency plans when necessary;
- the local authority to charge the operator for the preparation, review and testing of the off-site emergency plan; and
- the operator to provide information to the public.

It should be noted that if the amendment to the Directive on the Control of Major Accident Hazards Involving Dangerous Substances is passed as currently drafted, COMAH may well apply to both the trial and semi-commercial process. This is because the amendment brings the "processing and related storage" of minerals into the legislation. The current timescale for the amendment is September 2003, with the appearance of the revised UK Regulations set for 18 months after that date.

7.9 WASTE REGULATIONS

Relevant waste legislation includes Part II of Environmental Protection Act (EPA) 1990 and the Special Waste Regulations 1996. The EPA (amongst other things) places a duty of care upon the holder of the waste, to prevent the escape of the waste when it is in his care and to ensure that it is only transferred to another authorised person. This latter requirement involves the waste being transferred either to:

- a waste carrier registered under the Control of Pollution (Amendment) Act 1989;
- the holder of a Waste Management Licence issued under EPA; or
- a person undertaking a waste management activity that is exempt from waste management licensing under the EPA.

Waste that is not special waste should be transferred to any of the above with a Waste Transfer Note, which provides an accurate description of that waste. The Special Waste Regulations 1996 require wastes with certain hazardous properties to be transferred with a Special Waste Consignment Note. The procedure laid down by the Regulations requires the holder of the waste to notify the Environment Agency or the Scottish Environment Protection Agency at least three days before the waste is transferred. Information provided in the notification should include the registration number of the waste carrier and the waste management licence number of the site to which it is to be transferred.

It should be recognised that both the trial and semi-commercial operation would fall under the IPPC regime. As a result, the quantities and types of waste arising and their means of treatment/disposal, would be addressed under the IPPC permit. The treatment or disposal of any waste within the IPPC

installation would not require a Waste Management Licence, provided that it was permitted in the IPPC permit.

The storage and use of CO₂ gas separated from the UCG product gas in ECBM extraction at a separate site is not likely to be included in the IPPC installation and therefore would not be included in the permit. It is unclear however as to whether a Waste Management Licence would be required for this use of the CO₂ gas, but it is thought to be unlikely.

7.10 NOISE

In addition to the PPC Regulations 2000 and the PPC (Scotland) Regulations 2000, relevant noise controls include the BS 4142:1997 Method for Rating Industrial Noise Affecting Mixed Residential and Industrial Areas. This provides a means of determining the limit on incremental noise arising from a new development by consideration of the likelihood of complaint, and in the case of the UCG trial and semi-commercial operation would be implemented via the planning system. For settings where BS 4147:1997 is not applicable, the noise associated with a new development should be in accordance with the World Health Organisation recommended levels. In the case of the UCG trial and semi-commercial operations this approach would also be implemented via the planning system.

7.11 NOTIFICATION OF INSTALLATIONS HANDLING HAZARDOUS SUBSTANCES

The Notification of Installations Handling Hazardous Substances Regulations 1982 specify dangerous substances and the quantities of these substances that trigger an obligation to notify the Health and Safety Executive of their use three months before such use commences. It is likely that the quantities of substances used for the semi-commercial operation would exceed the quantities that trigger the notification obligation.

7.12 LICENSING AND ONSHORE DRILLING

7.12.1 Rights to Explore and Work the Coal

As there is no recent precedent for UCG operations in the UK, the licensing regime has not yet been fully defined. UCG operations bear some similarities to both underground coal mining and CBM activities. Consultation with the Coal Authority indicates that a hybrid licence specific to UCG operations may need to be developed. Any such licences would be subject to the operator being able to satisfy the Coal Authority in respect of its statutory duties and published policies and to the grant of planning permission and surface access rights for the proposed operations.

It is anticipated that the licences and agreements discussed in the following sections would be required to access and work (exploit) the coal.

Coal Authority Licences and Leases

The drilling and exploration boreholes and the subsequent injection and production wells would require the following licenses and leases from the Coal Authority:

- an Exploration Licence;
- an Operational Licence to work the coal; and
- a leasehold interest in the coal.

In addition, an Access Agreement from the Coal Authority may be necessary to pass through other seams.

Surface Access Rights

A Surface Access agreement would be required from the landowner.

Interaction Agreement

It will also be necessary to sign the Interaction Agreement. This agreement sets out a requirement for notification by an operator to any signatory of the Interaction Agreement, of any operation which may affect any coal mine or the interests of another operator with an interest in coal. The Interaction Agreement defines the responsibilities and liabilities of the operator associated with any potential interaction. Potential interactions include changes in:

- water flows or pressures;
- movement of mine gases;
- the structural integrity of the mine workings; and
- the effects of subsidence/interaction of other mines.

Petroleum Exploration and Development Licence

A key issue is whether a Petroleum Exploration and Development Licence (PEDL) will be required for UCG operations, as is required for the exploitation of CBM.

Under the Petroleum Act 1998 (relating to offshore exploitation) and the Petroleum (Production) (Landward Areas) Regulations 1995 (relating to onshore exploitation), a PEDL is required to “search and bore for and get petroleum”, where petroleum includes “any mineral oil or relative hydrocarbon and natural gas existing in its natural condition in strata”. Thus a PEDL would only be required if any natural gas (essentially CH₄) *existing in its natural condition* was produced to surface as a result of UCG operations. It seems likely however, that any naturally occurring methane associated with the coal would be consumed in the gasification process, and that any CH₄ produced to surface would result from the destructive distillation of the coal.

In consultation, the Oil and Gas Division of the DTI agreed that if no hydrocarbons in their natural state are produced, then no licence would be

required. However, the Health and Safety Executive took the view that any CH₄ originally associated with the coal would also be produced and that this is specifically included in the regulations governing onshore drilling, see below, as 'coal gas CH₄'.

The Coal Authority stated that, even if it was correct that no naturally occurring CH₄ would be produced, existing PEDL owners may see UCG as jeopardizing their interests in the coal and consequently adopt a different interpretation.

As PEDL's have already been granted over the majority of the onshore UK coal resources, the agreement of the existing PEDL owner would be required to undertake UCG at any selected onshore site if it was determined that UCG required a PEDL.

Methane Drainage Licence

The CH₄ drainage licence identified in the Petroleum (Production) (Landward Areas) Regulations 1995 relates to the removal of natural gas in the course of operations for making and keeping mines safe, and hence would not be applicable in the case of UCG.

7.12.2 Onshore Drilling, Well Construction and Abandonment

The principal Health and Safety Regulations governing onshore drilling operations are:

- Borehole Sites and Operations Regulations (BSOR) 1995;
- The Offshore Installations and Wells (Design and Construction) Regulations (DCR) 1996; and
- Health and Safety at Work Act 1974.

Regulation 3(c) of the COMAH Regulations 1999 indicates that, with regard to drilling operations, BSOR and COMAH are mutually exclusive: "(c) the activities of the extractive industries concerned with the exploration for, and the exploitation of, minerals in mines or by means of boreholes".

Application of BSOR and DCR

In the context of UCG, the BSOR and DCR Regulations will apply to an onshore well in Great Britain, or any activities in relation to it, only if it is drilled with a view to the extraction of petroleum.

Petroleum is defined as "any mineral oil or relative hydrocarbon and natural gas existing in its natural condition in strata, but does not include coal or bituminous shales or other stratified deposits from which oil can be extracted by destructive distillation".

It could be argued that that all the 'natural gas' originally contained in the coal seam is consumed in the gasification process, and that the CH₄ produced by

UCG is generated by the reaction of injected materials (oxygen and water) with hot coal, rather than being in its 'natural state'. However, it is the Health and Safety Executive's view that naturally occurring coal gas CH₄ would also be produced, as well as generated minerals, and thus the BSOR and DCR would apply. In any event, they would expect that the safety standards set by both sets of regulations, and particularly those in DCR applying to wells, should be met.

In terms of the regulations, a 'borehole site' means any site at which borehole operations are going to be undertaken, are being undertaken; or have been undertaken and at which there is a borehole, whether partly drilled or completed, which has not been abandoned. A 'borehole operation' refers to any activity in connection with the course of, furtherance of or cessation of the extraction of petroleum (or minerals) by a borehole, or prospecting with a view to such extraction.

Duty Holders

The Offshore Safety Division (OSD) of the Health and Safety Executive is the body with overall responsibility for ensuring compliance with the provisions of BSOR and DCR. However, the responsibilities in relation to subsequent gasification operations would be divided between Mines Inspectorate (MI), OSD and Field Operations Division (FOD). Inspection of the site/operation is likely to be a combined effort due to the nature of the operations and the hazards associated with the mixtures of flammable and toxic gases that will be produced.

The Duty Holder in relation to health and safety legislation is the person (Operator) appointed to supervise operations at a borehole site (BSOR) or well (DCR) or the (Concession) Owner if no operator has been appointed.

In practice, once it has been defined who has the rights to undertake the borehole operation, either they (the Owner) or a person (or company) they formally appoint, will be responsible for the health and safety aspects of the work under BSOR and DCR.

Provisions of SBOR and DCR

The BSOR and DCR notifications are the principal documentation required by the OSD. Notifications must be made to the OSD at least 21 days prior to the commencement or abandonment of drilling operations or any other operation where there is a significant risk of accidental release of fluids from a well. These notifications must specify all details of the planned well design and construction, proposed monitoring and control procedures, together with the geological and hydrogeological settings and all planned in-well processes and contingencies.

A two phase approval process is acceptable to OSD. The initial phase would cover all aspects of construction of the exploration, production and

interception wells. Detailed approval would subsequently be sought for ignition, gasification and associated activities. A standard well testing programme is required. At least two independent and effective barriers shall be established to contain the fluids. The well operator must appoint a competent and independent well examiner to review the design, construction, contingency, maintenance and process proposals for the borehole.

Abandonment of Wells

The OSD do not cover environmental hazards occurring after drilling and completion of the in-well processes, or at a distance from the boreholes. The normal responsibility of the OSD is to ensure that oil and gas wells are left in a safe condition and standard procedures are documented in the United Kingdom Offshore Operators Association (UKOOA) Guidelines for Suspension and Abandonment of Wells for the removal of casing, sealing and cement bond logging.

The Environment Agency will be the key authority in defining and monitoring abandonment arrangements. Coal gasification is explicitly included under the terms of the IPPC Regulations, and it is likely that additional monitoring boreholes will be required.

7.12.3 Health and Safety at Work Act 1974

The operator must ensure compliance with the Health and Safety at Work Act 1974 throughout the drilling and associated activity, as for any UK activity involving employed personnel.

8. AIR AND GLOBAL EMISSION ISSUES

The operation of a trial UCG plant or a semi-commercial power plant using UCG product gas as fuel will result in discharges to the atmosphere of the products of combustion. These emissions, primarily the classical air pollutants sulphur dioxide, oxides of nitrogen and CO will be subject to the legislative and regulatory controls described in the previous section. Carbon dioxide emissions, in addition to falling within the remit of the greenhouse gas emissions trading regulations will also be a factor in the BAT assessment under the IPPC regulations.

This section evaluates the ground level pollutant concentrations that may result from a UCG trial in which product gas is combusted, and a semi-commercial UCG power plant operating on product gas. For the purpose of this assessment it is assumed that the UCG trial reactor has a maximum product gas production rate of 400 tonnes per day. It is envisaged that semi-commercial operation will maintain a gas production rate that will allow power generation in the range 40 to 100 MWe. The upper limit of this range has been selected for assessment, as this case will have the highest emissions.

The assessed designs are described in detail below. These notional designs are intended to give reasonable estimates of emissions for the scenarios selected, but are not to be regarded as being indicative of model engineering specifications or representative of BAT under the IPPC regime. There follows an account of the dispersion modelling of the emissions and the evaluation of the results obtained in the context of established air quality criteria. Appendix I documents these criteria.

8.1 EXAMPLE UCG TRIAL AND SEMI-COMMERCIAL PLANT DESIGNS

The product gas specification used to estimate emissions for both designs relates to bituminous coal, which is most representative of the UK. Lignite will yield a product gas of a somewhat different composition. These differences were found not to be significant for the purpose of this example assessment.

8.1.1 Example UCG Trial Design

The UCG trial is envisaged to operate over a period of up to nine months. It has been assumed that product gas will be fed directly into a combustion unit without prior treatment or removal of water vapour. The peak daily production of 400 tonnes of product gas is not likely to occur for extended periods during that time. However, this maximum flow rate has been assessed. It is envisaged that the UCG trial site would require a minimum area of 500m by 200m.

For the dispersion modelling of the full load case, the UCG product gas is assumed to be satisfactorily combusted without additional support fuel such as natural gas. Were additional CH₄ used, ground level concentrations of pollutants would decrease due to the additional volume of flue gas and the resultant enhanced dispersion.

A standard bituminous coal specification was used to derive a product gas composition, (type 800–900, high volatiles, non-caking, ~ 25MJ/kg). This coal specification included sulphur, chlorine and nitrogen contents of 2.0%, 0.8% and 0.2% by weight respectively. The UCG product gas composition and mass flow rates are shown in Table 8.1. The mass flows relate to the peak daily production of 400 tonnes. Two thirds of the mass of the product gas is CO₂ and water. CO, H₂ and CH₄ are present in similar molar proportions and there are small amounts of hydrogen sulphide, hydrogen chloride and nitrogen.

Substance	Mol Mass	Mass %	Mol%	Tonnes /day	kg/h	kmol/h
H2O	18.016	22.65	28.37	90.59	3774	209.5
CO2	44.010	46.10	23.64	184.39	7683	174.6
CO	28.010	19.15	15.43	76.60	3192	113.9
H2	2.016	1.66	18.58	6.64	277	137.2
CH4	16.042	9.43	13.26	37.70	1571	97.9
H2S	34.086	0.69	0.46	2.78	116	3.4
HCl	36.458	0.07	0.04	0.26	11	0.3
N2	28.020	0.26	0.21	1.04	43	1.6
Mixed Gas	22.569	100.00	99.99	400.00	16667	738.4

Table 8.1 - UCG Product Gas Composition and Flow Rates

The UCG product gas will be combusted and the resultant flue gases discharged directly to the atmosphere. The type of combustor will influence the process building dimensions, but it is assumed that the building will be five metres high and 10m by 20m. The flue gas properties are shown in Table 8.2. The pollutant emission rates shown in Table 8.3 are derived from the product gas composition except for oxides of nitrogen, which are based on an upper limit of 300mg/Nm³, which can be achieved by the type of combustor that would be employed.

Parameter	Value
Flue diameter at exit point, m	2.60
Exhaust gas temperature, °C	900
Exhaust gas exit velocity, m/s	25
Actual exhaust gas flow rate, m ³ /s	132.5
Moisture content, %	10.35
Oxygen content, (dry basis) %	13.81
Normalised exhaust gas flow rate, Nm ³ /s (273 K, dry, 101.3 kPa, without oxygen correction)	27.65

Table 8.2 - UCG Trial Flue Gas Characteristics

Pollutant	Emission Rate g/s
Sulphur dioxide	60.45
Hydrogen chloride	3.06
Oxides of nitrogen	8.30

Table 8.3 - UCG Trial Pollutant Emission Rates

8.1.2 Example Semi-commercial Plant Design

The example semi-commercial plant considered in this assessment represents the upper end of the range 40 to 100 MW_e. Assuming a 49% efficiency of the combined cycle gas turbine (CCGT) plant, 100 MW_e power generation would require 1520 tonnes of UCG gas per day. However, it would be advisable to incorporate a hydrogen sulphide removal stage prior to the gas turbines. Hydrogen sulphide removal efficiency has been taken to be 95%. This process would also completely remove hydrogen chloride. Incorporation of gas cleaning implies an overall efficiency of 45% and an increased fuel requirement of 1660 tonnes per day to provide the rated power output. It is envisaged that the semi-commercial site would require a minimum area of 550 m by 250 m.

The flue gas characteristics of the plant are shown in Table 8.4. The pollutant emission rates are shown in Table 8.5. The Large Combustion Plant Directive 2001/80/EC specifies an oxides of nitrogen emission limit for gas turbines using gaseous fuel other than natural gas of 120mg/Nm³ (15% oxygen content). This is the basis of the emission rate used in the dispersion modelling, but in practice this type of plant may well achieve 80mg/Nm³ oxides of nitrogen. Again for the purposes of setting a stack height and subsequent dispersion modelling, the plant is assumed to be housed in a structure fifteen metres high and 30m by 30m.

Parameter	Value
Flue diameter at exit point, m	3.20
Exhaust gas temperature, °C	150
Exhaust gas exit velocity, m/s	18
Actual exhaust gas flow rate, m ³ /s	144.6
Moisture content, %	14.18
Oxygen content, (dry basis) %	10.78
Normalised exhaust gas flow rate, Nm ³ /s (273 K, dry, 101.3 kPa, 15% O ₂ dry basis)	136.0

Table 8.4 - UCG Semi-commercial Flue Gas Characteristics

Pollutant	Emission Rate g/s
Sulphur dioxide	12.58
Oxides of nitrogen	16.32

Table 8.5 - UCG Semi-commercial Pollutant Emission Rates

8.2 DISPERSION MODELLING

For each of the generic plant designs, the flue gas characteristics, pollutant emission rates and notional building dimensions were used to calculate minimum stack heights. The stack height calculation was carried out using

the procedure described in Her Majesty's Inspectorate of Pollution (HMIP) Technical Guidance Note D1 (HMIP,1993). Medium values of background pollutant concentrations were used as given in the guidance note for an "urban area of limited size with parkland or largely rural surroundings".

The emissions from the proposed plant were modelled using the US model AERMOD version 99351. This model is the result of many years development by the USEPA and the American Meteorological Society. It has been developed as a regulatory model that incorporates the current understanding of atmospheric physical processes. This is referred to as 'new generation' meteorology, and the UK Environment Agency recommends the use of such models.

Four years of meteorological data from Birmingham Airport were used as being reasonably representative of large parts of the country for the purpose of this generic study. The hourly sequential data was processed to represent the site using a surface roughness of 1.0m. The meteorological data file contains over 35,000 hourly records, and hence characterises extreme meteorological events and long-term average conditions. There is no significance attached to the actual years used. The joint frequency distribution of wind speeds and direction is depicted as a wind rose diagram in Figure 8.1.

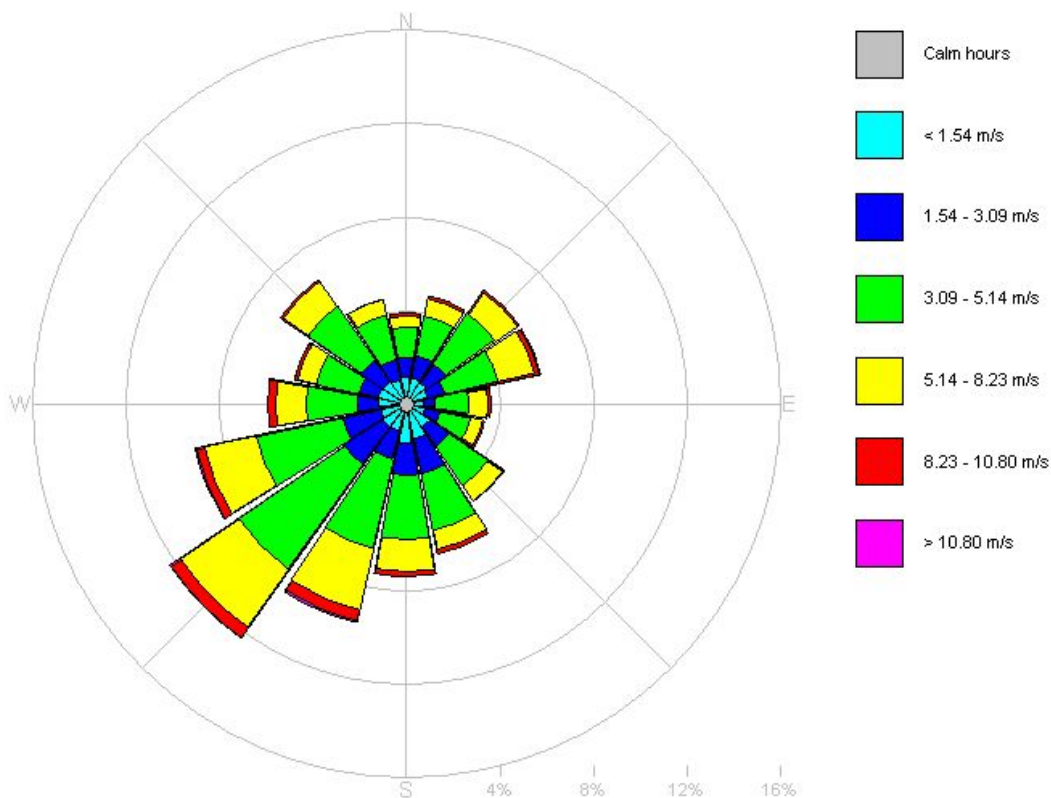


Figure 8.1 - Wind Rose Diagram (courtesy of WS Atkins)

The AERMOD study included direction specific building downwash effects for the UCG trial and semi-commercial plant buildings. The dispersion modelling was carried out using a receptor grid spaced at 50m intervals. For the UCG trial a 1.5 by 1.4km grid of 899 receptors was used. This was extended for the semi-commercial plant to allow for the increased dispersion from the higher stack and a 2.0 by 1.9km grid of 1,599 receptors was used.

AERMOD reports the highest hourly, daily and period averages found using the four years of meteorological data. The maximum hourly result at each receptor is therefore the highest in over 35,000 hours processed, and the maximum daily result the highest in over 1450 days. Similarly, the long term results show the four year period average. This may be regarded as a robust estimate of the annual mean result at each receptor.

For both the UCG trial and semi-commercial operation, a unit mass pollutant emission rate was modelled. Ground level pollutant concentrations are proportional to emission rate. Results for specific pollutants may be scaled by the appropriate emission rate and these results are tabulated below. To demonstrate the spatial distribution of the emissions, the unit mass emission rate results are also shown as contour plots.

8.2.1 UCG Trial Plant

The stack height calculation for the UCG trial plant gives a minimum stack height of 13m using the above information regarding flue gas characteristics, pollutant emissions rates and building dimensions. The plant and stack dimensions used in the modelling are shown schematically against the 50 m receptor grid in Figure 8.2.

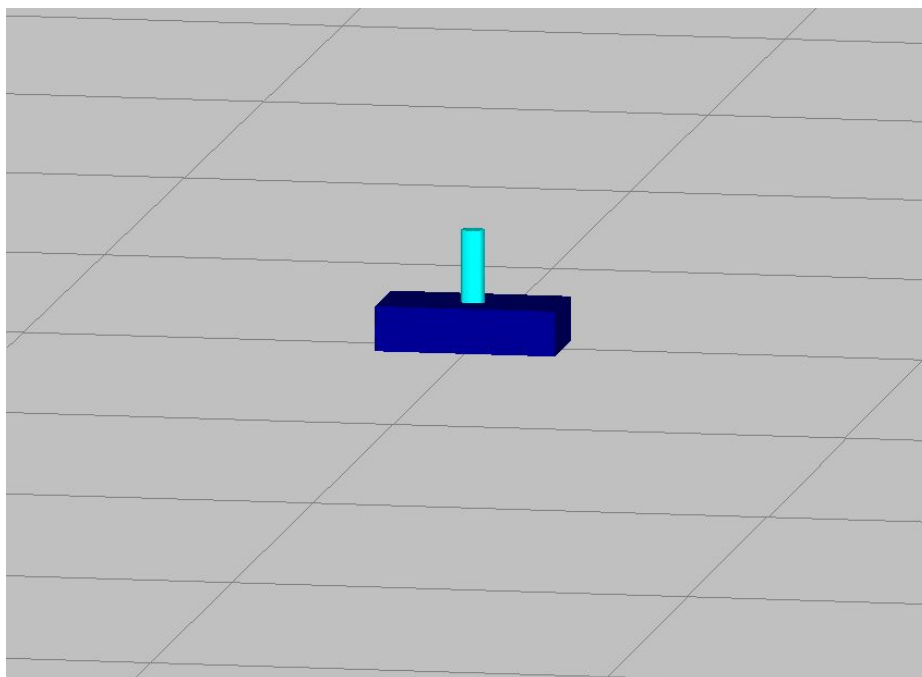
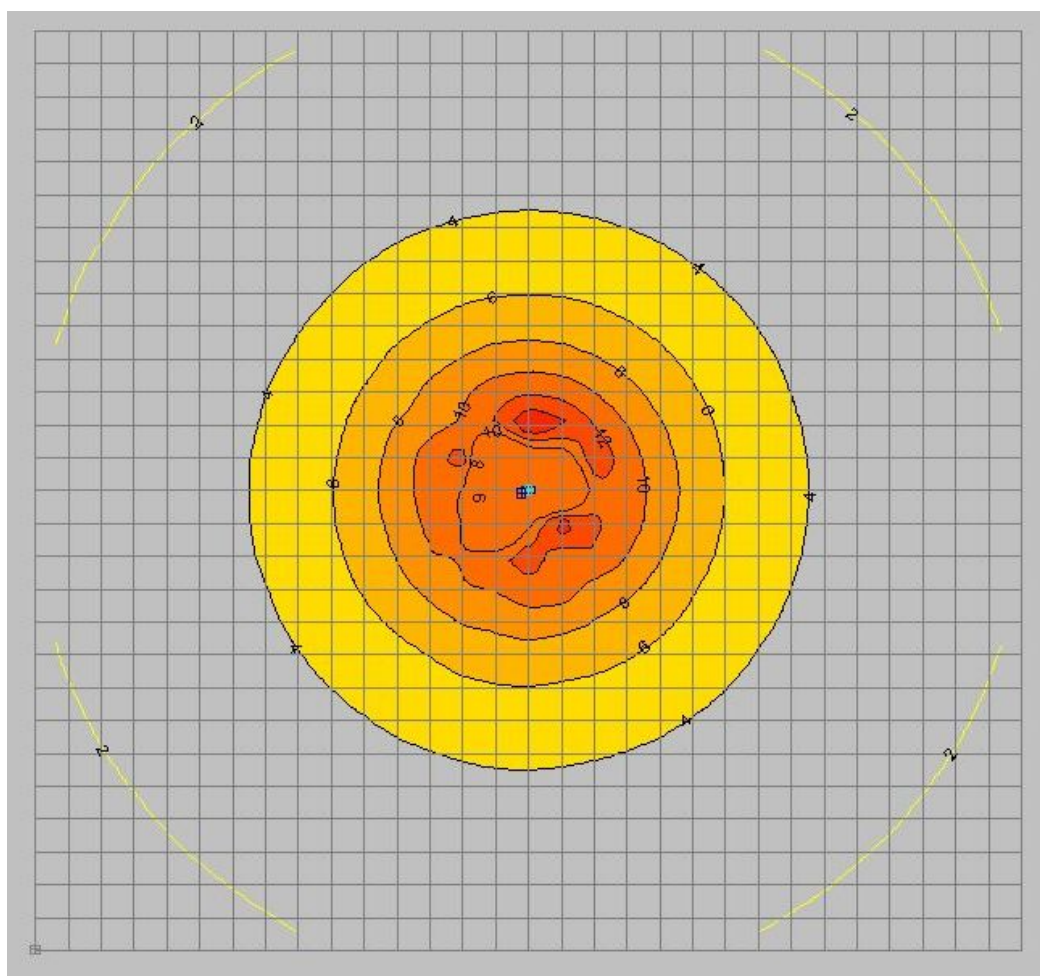


Figure 8.2 - UCG Trial Plant (courtesy of WS Atkins)

The unit mass pollutant emission rate modelled results in the maximum hourly, maximum daily and period average concentrations which are shown in Figures 8.3, 8.4 and 8.5 respectively.

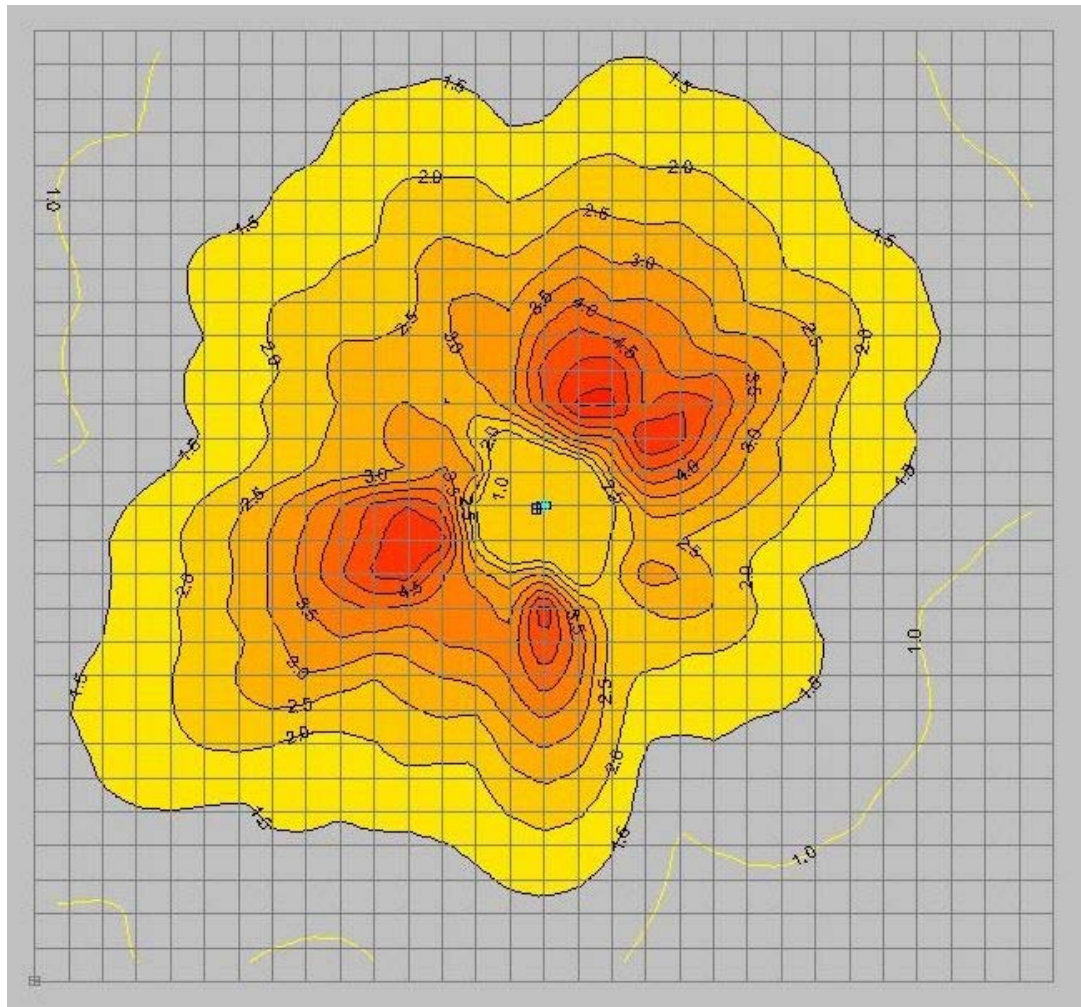
The absolute maximum hourly concentration is $16.4\mu\text{g}/\text{m}^3$, at a location 100m to the north of the stack. Maximum hourly concentrations are over $10\mu\text{g}/\text{m}^3$ in all directions at distances of between 90 and 180m from the source. The influence of the plume is quite localised and concentrations fall to below $5\mu\text{g}/\text{m}^3$ at a distance of 350m from the stack. .



Stack height 13 m

Figure 8.3 - UCG Trial Maximum Hourly Concentrations, $\mu\text{g}/\text{m}^3$ (courtesy of WS Atkins)

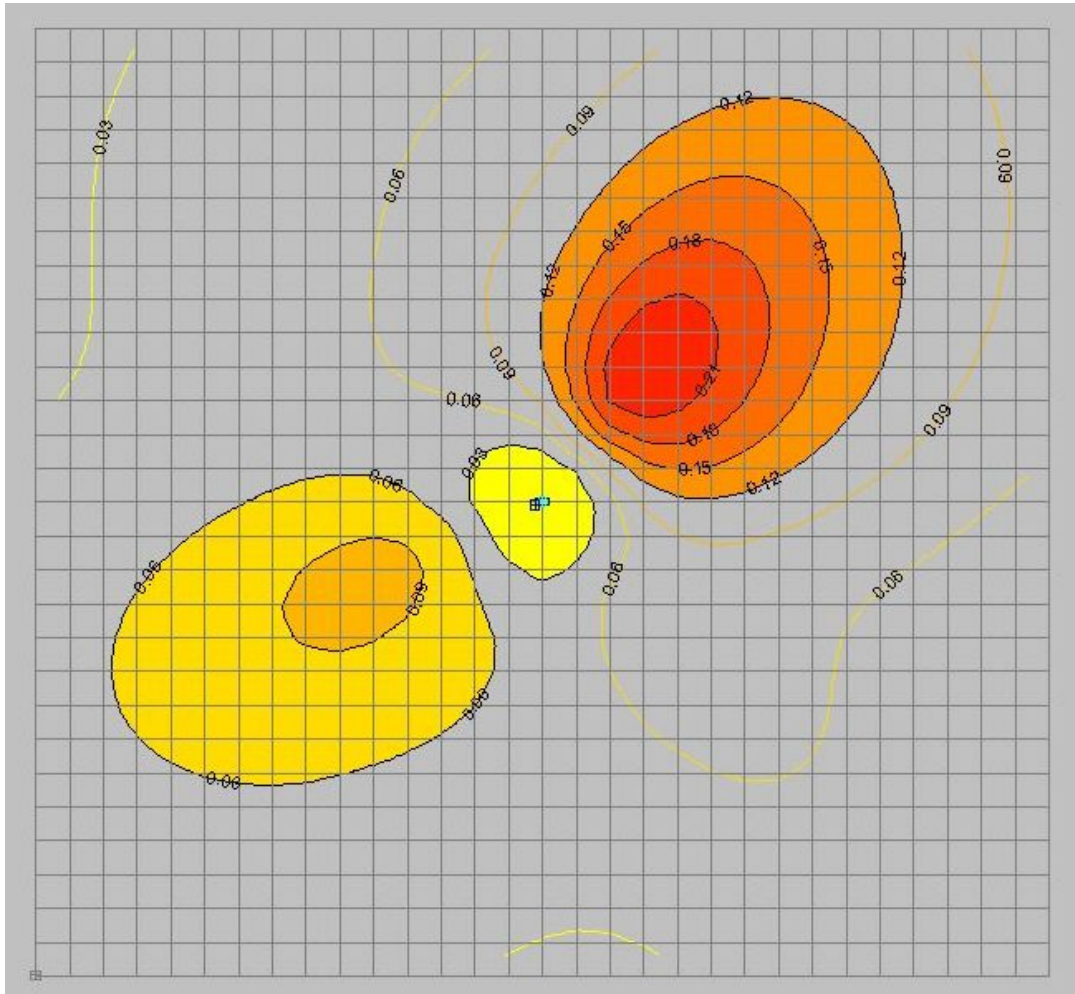
The absolute maximum daily concentration is $5.7\mu\text{g}/\text{m}^3$, 180m to the north-east of the stack. Maximum daily concentrations may exceed $2.5\mu\text{g}/\text{m}^3$ in all directions other than the south-east at distances of between 90m and 500m from the source. The areas of higher concentrations within this zone, such as those to the south and the south-west, reflect persistent meteorological conditions that tend to arise in the UK albeit relatively infrequently.



Stack height 13 m

Figure 8.4 - UCG Trial Maximum Daily Concentrations, $\mu\text{g}/\text{m}^3$ (courtesy of WS Atkins)

In contrast to the short term model results, the period average concentrations reflect the frequency of wind speeds and directions shown in the wind rose diagram. The highest period average concentration is $0.24\mu\text{g}/\text{m}^3$, at a location 250m to the north of the stack. The surrounding area in which concentrations may exceed half that value is limited, extending some 500 to 600m across. There is a secondary area to the south-west of the stack where concentrations just reach $0.1\mu\text{g}/\text{m}^3$.



Stack height 13 m

Figure 8.5 - UCG Trial Period Average Concentrations, $\mu\text{g}/\text{m}^3$ (courtesy of WS Atkins)

Results

Table 8.6 shows the maximum ground level concentrations that would result from the pollutant emission rates given in Table 8.3.

Pollutant	Averaging Period	Maximum Contribution	Criteria	Maximum contribution as % of criteria	
Nitrogen dioxide*	Maximum 1-hour	27.3	200	Source AQS objective †	13.6
	Annual mean	0.4	40	AQS objective	1.0
Oxides of nitrogen	Annual mean	2.0	30	AQS objective	6.6
Sulphur dioxide	Maximum 1-hour	992.3	350	AQS objective †	283.5
	Maximum 24-hour	344.1	125	AQS objective †	275.3
	Annual mean	14.5	50	WHO guideline	29.0
Hydrogen chloride	Annual mean	14.5	20	AQS objective	72.4
	Maximum 1-hour	50.2	800	EAL	6.3
	Annual mean	0.7	20	EAL	3.7

* See text, NO to NO₂ conversion taken to be 20%.

† See Appendix *Air Quality Criteria* for frequency of permitted exceedances.

Table 8.6 - UCG Trial Dispersion Model Results Summary

The oxides of nitrogen emissions are almost entirely of nitric oxide, which slowly reacts with ozone and other gases in the atmosphere to form nitrogen dioxide. Within the time scales of the plume reaching receptors in the study area, only a small fraction of the oxides of nitrogen will have converted to nitrogen dioxide. The proportion converted depends on a number of factors such as the meteorological conditions, the availability of reactive species in the atmosphere and the time of day. However, as an indication the Department of the Environment and Transport (DETR) (Pollution Specific Guidance, LAQM, TG4(98)) advised local authorities to assume that the average ratio nitrogen dioxide/oxides of nitrogen at the point of maximum impact of a plume is 0.2.

On that basis, maximum hourly concentrations of nitrogen dioxide are low, being less than 15% of the Air Quality Strategy (AQS) Objective. The trial is likely to last less than nine months and will only operate at the load modelled for a short period during that time. The maximum values reported are therefore very conservative.

The maximum short term hydrogen chloride concentration is less than 7% of the Environment Agency EAL.

Maximum short-term sulphur dioxide levels could theoretically be over two and a half times the air quality criteria. Although the location of maximum ground level concentration may be within the site boundary, such high concentrations would be a concern, even given the unlikely coincidence of full load operation and the least favourable meteorological conditions in four years.

These results indicate the need for a stack height sensitivity study as part of any proposed future UCG trial, as relatively modest increases in stack height may prove to be advantageous in terms of mitigating short term sulphur dioxide concentrations. As an indication, a stack height of 26 m for the example trial design was modelled. This was found to reduce maximum hourly concentrations by 69%, maximum daily concentrations by 52% and period average concentrations by 39%. This particular example would result in the maximum hourly concentration meeting that criterion and the maximum daily concentration marginally exceeding the relevant criterion.

8.2.2 Semi-commercial Plant

Given the above assumptions regarding flue gas characteristics, pollutant emissions rates and building dimensions, the stack height calculation for the UCG semi-commercial plant gives a minimum stack height of 33m. This stack height was rounded up to 35m for dispersion modelling. The plant is shown schematically against the 50m receptor grid in Figure 8.6.

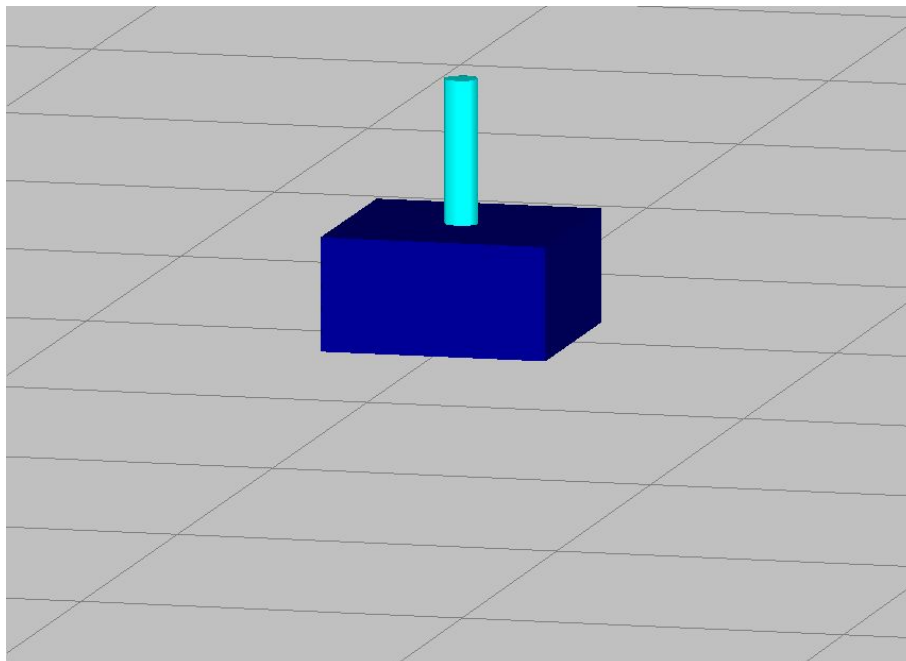
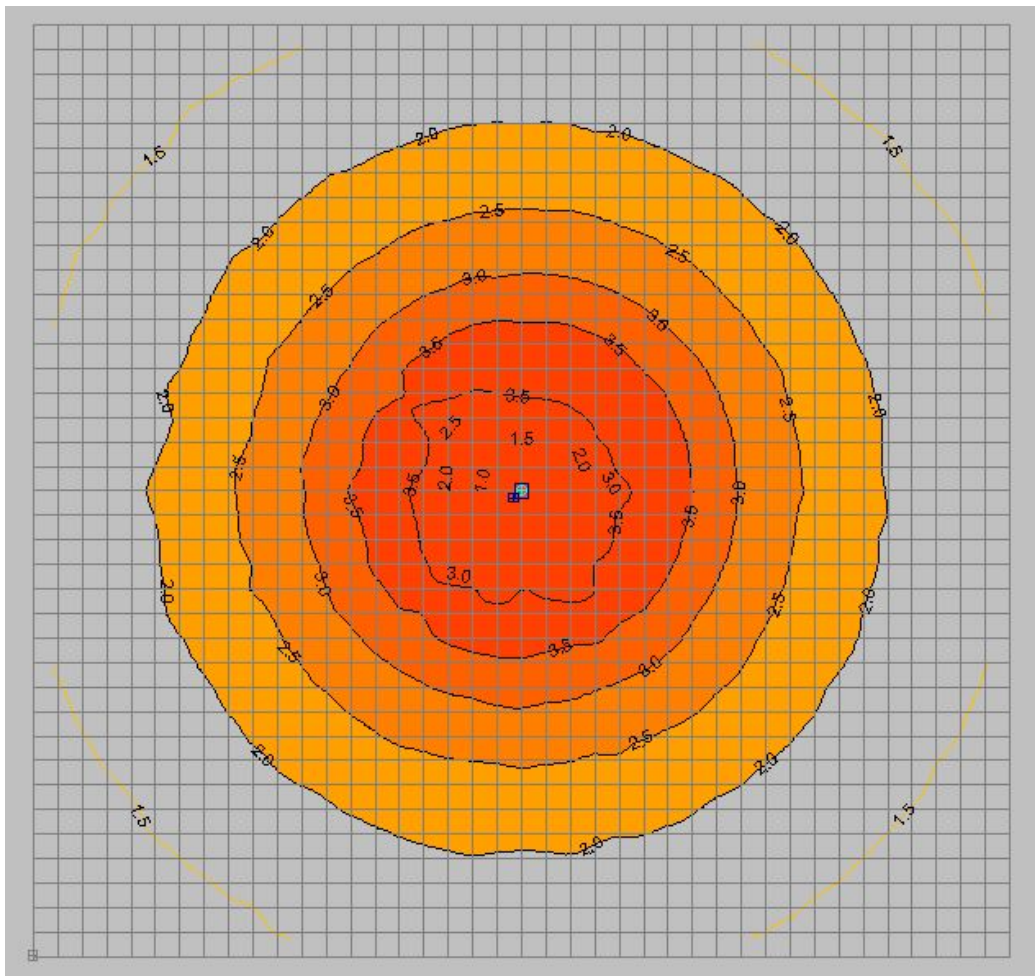


Figure 8.6 - Semi-commercial Plant (courtesy of WS Atkins)

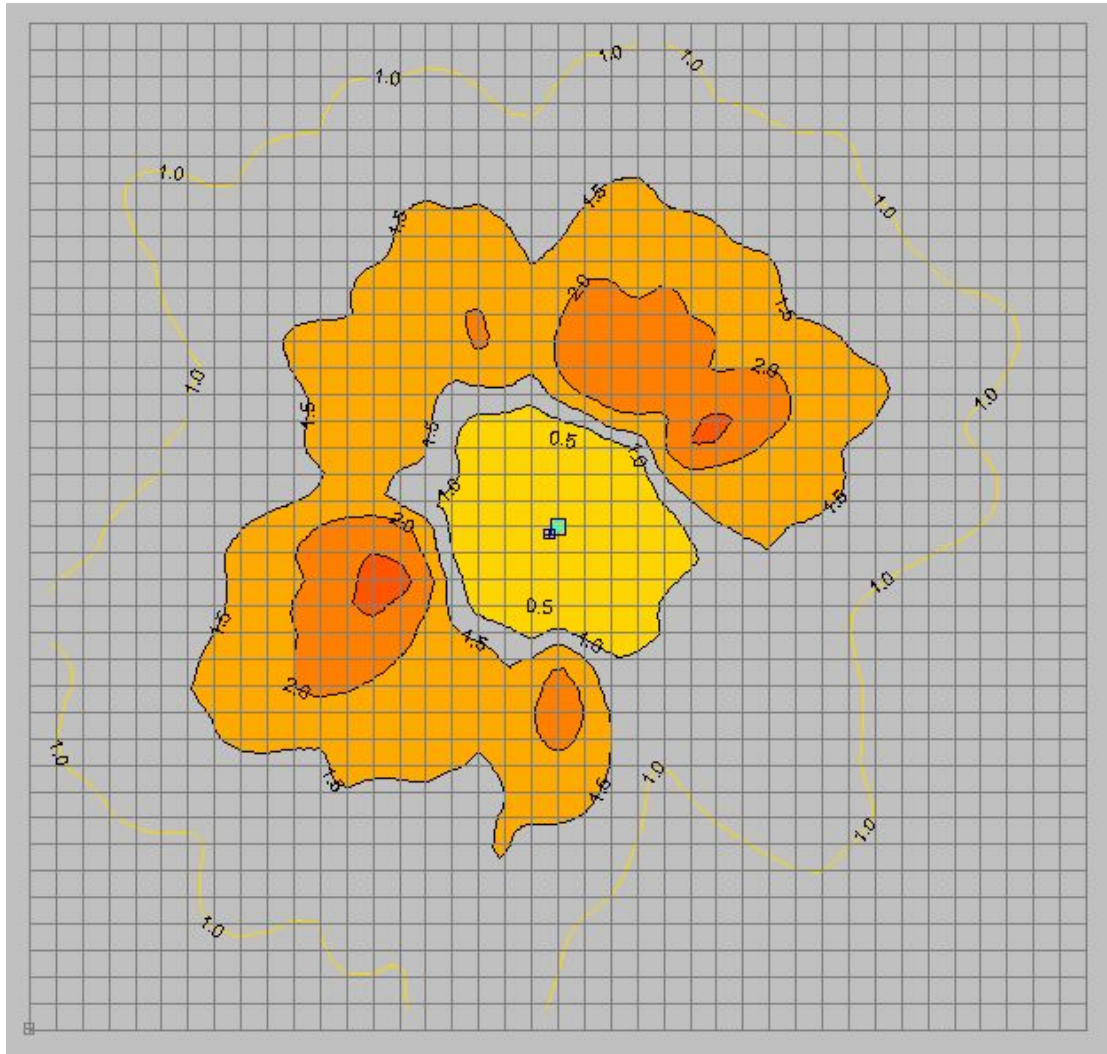
The unit mass pollutant emission rate modelled results in maximum hourly, maximum daily and period average concentrations shown in Figures 8.7, 8.8 and 8.9 respectively. Figure 8.7 shows that the highest hourly concentrations rise with increasing distance from the source and exceed $3.5\mu\text{g}/\text{m}^3$ at distances of between 200 and 350m. The absolute maximum hourly concentration of almost $4.0\mu\text{g}/\text{m}^3$ is at a location 250 m to the north of the stack. Hourly concentrations fall to below $1.5\mu\text{g}/\text{m}^3$ at a distance of 1000m from the stack.



Stack height 35 m

Figure 8.7 - Semi-commercial Maximum Hourly Concentrations, $\mu\text{g}/\text{m}^3$ (courtesy of WS Atkins)

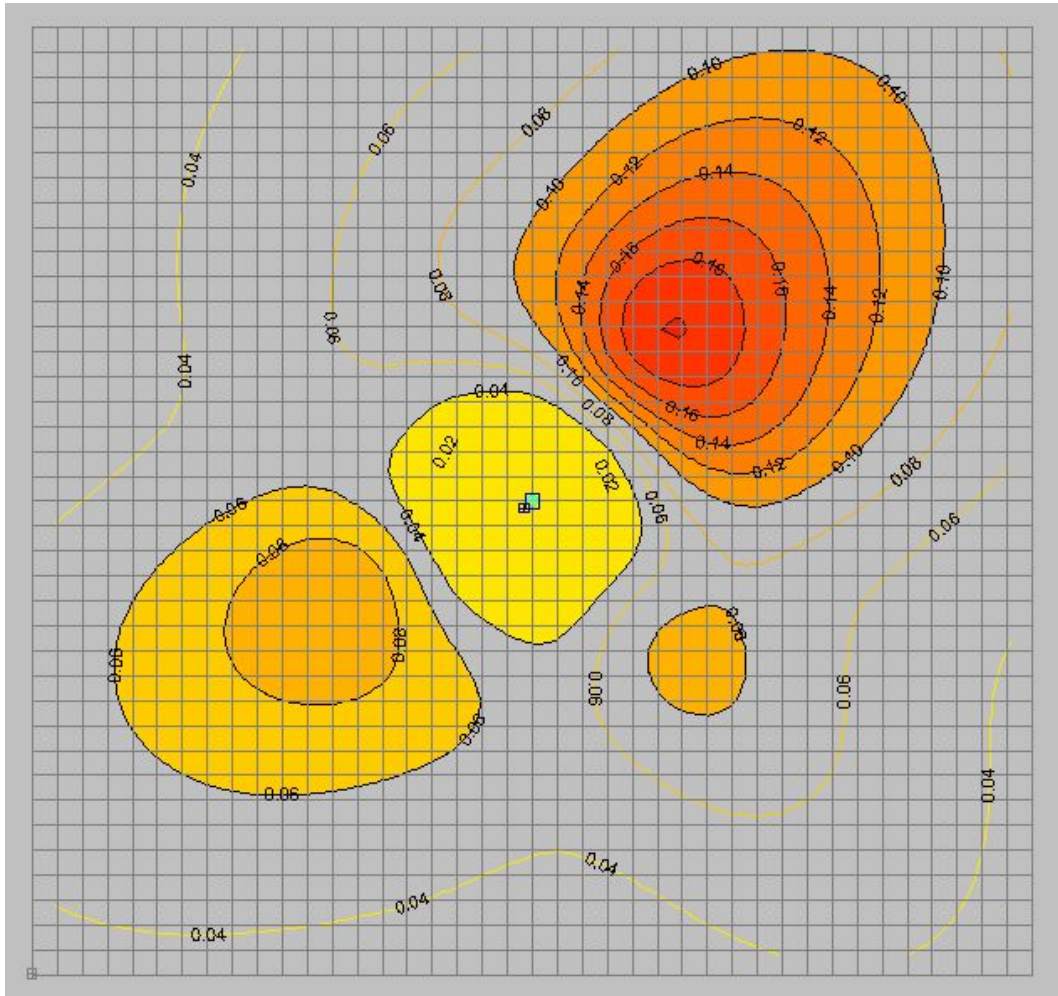
Figure 8.8 shows the absolute maximum daily concentration is $2.7\mu\text{g}/\text{m}^3$, 325m to the south-west of the stack. There is an area to the north-east where the daily average concentration reaches $2.6\mu\text{g}/\text{m}^3$.



Stack height 35 m

Figure 8.8 - Semi-commercial Maximum Daily Concentrations, $\mu\text{g}/\text{m}^3$ (courtesy of WS Atkins)

Figure 8.9 shows the highest period average concentration of $0.20 \mu\text{g}/\text{m}^3$, at a location 450 m to the north-east of the stack. There is a secondary area to the south-west of the stack where concentrations approach $0.01 \mu\text{g}/\text{m}^3$.



Stack height 35 m

Figure 8.9 - Semi-commercial Period Average Concentrations, $\mu\text{g}/\text{m}^3$ (courtesy of WS Atkins)

Results

Table 8.7 shows the maximum ground level concentrations that would result from the pollutant emission rates given in Table 8.5.

Pollutant	Averaging Period	Maximum Contribution	Criteria	Source	Maximum contribution as % of criteria
Nitrogen dioxide*	Maximum 1-hour	13.0	200	AQS objective [†]	6.5
	Annual mean	0.7	40	AQS objective	1.6
Oxides of nitrogen	Annual mean	3.3	30	AQS objective	6.5
Sulphur dioxide	Maximum 1-hour	50.0	350	AQS objective [†]	14.3
	Maximum 24-hour	33.8	125	AQS objective [†]	27.1
	Annual mean	2.5	50	WHO guideline	5.1
	Annual mean	2.5	20	AQS objective	12.7

* See text, NO to NO₂ conversion taken to be 20%.

[†] See Appendix *Air Quality Criteria* for frequency of permitted exceedances.

Table 8.7 - UCG Semi-commercial Operation Model Results Summary

Maximum hourly concentrations of nitrogen dioxide are less than 7% of the AQS Objective, on the basis of a 20% conversion rate of nitric oxide to nitrogen dioxide. Annual mean concentrations due to the plant will be less than 2% of the criterion.

The annual mean and maximum hourly and maximum daily sulphur dioxide concentrations both approach 15% of the respective objective values for the protection of human health and vegetation. The maximum daily sulphur dioxide concentration approaches 30% of the criterion.

8.3 GLOBAL EMISSIONS

This section discusses the CO₂ emissions from UCG plant in the context of the emissions from established technology. The high CO₂ content and relatively low calorific value of the UCG product gas leads to an unfavourable comparison with other fossil fuel technologies in terms of global warming potential. Theoretically, CO₂ may be removed either from the product gas pre-combustion or from the flue gas post-combustion. The latter option would be feasible in a CO₂ rich scenario where combustion is supported by oxygen rather than air. Earlier work has focussed on pre-combustion removal of CO₂, and the potential implications in terms of plant efficiency of this approach are

addressed below. The options for subsequent long term underground storage of the gas are set out in Section 6.

Hydrogen Sulphide Removal and CO₂ Sequestration

Conventional combustion plants are typically 33 to 35% efficient in the conversion of fuel to electricity. IGCC plants offer the prospect of boosting efficiencies to 45 to 50% in the short-term and potentially to nearly 60% with technological advancements. Replacement of the gasifier by underground gasification has the potential to improve the both cost and peripheral environmental performance by removing the extractive operation otherwise required to provide the feedstock.

The gasification of coal results in a synthesis gas high in CO₂ and often high in hydrogen sulphide depending on the type of coal from which the gas is derived. However, decreasing the environmental impact of these gases reduces overall plant efficiency. A power generation scheme using UCG product gas in a combined cycle (UCGCC) would have CO₂ emissions comparable with that from a pulverised coal power generation station fitted with flue gas desulphurisation (FGD) (Laughlin and Summerfield, 2000).

However, one of the major advantages that UCG has over an FGD power station is the potential for CO₂ capture and sequestration, which is facilitated by the high pressure and concentration of CO₂ in the UCG product gas. If UCGCC was combined with CO₂ capture and sequestration, CO₂ emissions to atmosphere could be reduced to levels comparable with a natural gas fuelled combined cycle power station, which currently has the lowest CO₂ emission level.

Post-combustion capture of low concentrations of CO₂ (typically 14%) in a pulverised coal power generation station fitted with FGD, requires the handling of a large volume of gas, necessitating large and expensive equipment. A further disadvantage of low CO₂ concentrations is that powerful solvents have to be used and the consequent regeneration of these solvents, releasing the CO₂, requires a large amount of energy. A higher concentration and pressure of CO₂ reduces the size of the capture equipment required and enables solvents with lower energy penalties for regeneration to be used. This can be achieved by pre-combustion capture, which could be applied to the product gas from an underground gasifier.

A shift reactor can further enhance CO₂ concentration. The process involves reacting the CO in the product gas with steam in a catalytic shift conversion stage which converts CO to CO₂, and produces more H₂. The CO₂ is separated from the product gas by a physical solvent (e.g. the Selexol process) and the remaining H₂ and CH₄ are combusted in a gas turbine combined cycle plant.

Hydrogen sulphide requires removal and stripping from the flue gas, followed by sulphur recovery in either a Claus plant or an alternative such as a LO –

CAT unit. This process results in approximately a 5% loss of net electrical power generation.

Removal of CO₂ requires absorption and stripping from the flue gas, followed by drying and compression for storage purposes. This process results in a 14 to 17% loss of net electrical power generation. Sequestration of CO₂ requires injection of the gas into the coal face, the overall process of CO₂ removal and sequestration would probably result in approximately a 20 % loss of net electrical power generation.

For a 100 MW_e rated coal-syngas plant, Table 8.8 indicates the effect that hydrogen sulphide removal and CO₂ sequestration have on efficiency. Of more concern than the raw electrical efficiency however is the capital cost of equipment to carry out the gas cleaning process.

Plant Setup	Plant net electrical output (MWe)	Plant overall efficiency %
IGCC or UCG Plant direct combustion of gas	100	50
IGCC or UCG Plant + H ₂ S removal	95	47.5
IGCC or UCG Plant + H ₂ S removal + CO ₂ sequestration	75	37.5

Table 8.8 - Overall Plant Efficiency with H₂S Removal and CO₂ Sequestration

To the basic generating island must be added a solvent absorption plant and the sulphur recovery system if hydrogen sulphide is to be removed. With increasing sulphur content in the coal, pre-treatment of the syngas becomes more favourable economically than post-combustion abatement of oxides of sulphur. The ability of UCG plant to utilise high sulphur coal is a particular advantage of this technology, as the high pressure and high sulphur content of the product gas facilitates low cost sulphur removal and recovery.

As described above, for CO₂ sequestration, the CO₂ can be removed from the syngas prior to combustion and the process enhanced by the use of a shift reactor. The resultant H₂ rich gas fuels the generating plant. This would require additional plant for purification, compression and liquefaction of the CO₂, with its attendant operational and maintenance costs.

The thermal efficiency does not look unattractive, even including CO₂ capture, as the overall efficiency is comparable to the average of the UK generating portfolio. Nevertheless, in the current energy market the capital spend required to achieve the environmental aims may render the 'economic efficiency' prohibitive, in terms of cost per megawatt of plant capacity, when compared with alternative technologies such as gas-fired CCGT. However, in terms of utilising otherwise unavailable fossil fuel reserves whilst minimising

emissions of gases contributing to global warming, the technology appears to be advantageous, particularly in a future market driven by carbon emissions trading obligations.

9. BEST PRACTICE

Environmental best practice for site selection, site investigation, construction, operation, shut down and monitoring of a trial or semi-commercial UCG operation is provided within a separate Best Practice Guide document. It should be noted that monitoring and mitigation measures have not been discussed within the body of this report as they are described in detail within the Best Practice Guide.

The Best Practice Guide contains:

- the planning, groundwater and general environmental factors that should be considered during the site selection and site investigation stages of a UCG development;
- suggested methods and guidance for evaluating risks to groundwater;
- general environmental considerations for construction and operation of the site;
- UCG specific mitigation measures for construction, operation and shutdown/restoration of the site (eg drilling methods, process control, waste water treatment etc); and
- post operation monitoring requirements and options.

The document was developed from three main sources of information:

- the technical information gathered and presented within this report;
- UK regulatory requirements that affect site selection, operation and mitigation measures, the majority of which are discussed within this report; and
- standard best practice environmental guidance from other relevant industries.

The third group of inputs was obtained from a wide variety of sources. A brief summary of those sources and the relevance of the information obtained is provided below:

- UK coal mining - most of the knowledge of coal and associated strata was obtained from UK coal mining sources, as well as all of the information on strata impacts caused by caving of the reactor. CBM information was of limited use due to the differences in gas transport models, although some of the information on coal/gas response was obtained from CBM sources;
- UK onshore oil and gas drilling - information on well construction and integrity was provided by BP Wytch Farm operatives and published gas industry sources. Information on waste minimisation and drill cuttings

was also obtained. The methods used for geological and hydrogeological assessment by these industries was of limited use due to the differences in relevant geology and the fact that escape of oil/gas via natural pathways is not usually a significant consideration;

- Nirex provided the most relevant and useful information on gas transport models;
- USEPA provided information on its 'Underground Injection Control Programme'. This contained guidelines on injection well design, well integrity monitoring and the selection of suitable strata for controlled underground disposal;
- Environment Agency standard practice for oil storage and pollution prevention guidelines (PPG) were used for surface mitigation measures; and
- CIRIA construction best practice guidance was used for surface mitigation measures and waste storage.

10. CONCLUSIONS

10.1 TECHNICAL FACTORS AND EVALUATION OF RISKS TO GROUNDWATER

Environmental information gathered from previous trials in other countries has shown that shallow UCG can pose a potentially significant risk to groundwater. Most of the trials that have been carried out in other countries have been much shallower than the proposed UK activities, but they have been valuable in demonstrating the mechanisms through which UCG could pose a risk both in terms of gas escapes and emission of leachates.

For a suitable deep UK site, the risk to water resources such as major overlying aquifers is likely to be very low. However, UK legislation (based on EU Directives) means that the release of many of the contaminants produced, including the main contaminants such as ammonia and phenols, to any groundwater is prohibited. Legislative options are available that can address this issue and permit UCG operations based on exemption clauses within the existing Groundwater Regulations. This exemption clause centres on the definition of a 'permanently unsuitable' zone of groundwater where quality and yield are such that the groundwater cannot be realistically used as a resource in future. If this zone can be agreed with the regulator, then it should be possible to permit emission of contaminants from UCG as long as it can be shown that they will remain within this zone. Therefore, whilst this approach is likely to require reasonably onerous risk assessments, authorisation of UCG with respect to groundwater should be feasible at a deep site in the UK.

Significant uncertainties remain about the generation and concentration of underground contaminants and the processes appear to be dependent on site characteristics. Emission estimates for UCG are particularly difficult due to the fact that both the gases and leachates emitted underground may be involved in further interactions between the gaseous and liquid phases. The

most significant occurrences of contamination from previous trials in shallow seams that have been recorded in any detail appear to have been caused by gas escapes during or immediately after gasification. Gas escapes also entrained contaminants from within the pyrolysis zone around the reactor as well as causing contamination due to the nature of the product gases themselves. This sort of event is largely controllable by suitable reactor operation at a deep site, which will allow operating pressures to be maintained below hydrostatic pressure and hence prevent gas escapes. Because of the uncertain nature of the reaction and caving process and the difficulty in obtaining detailed information at depth, it is likely that any site evaluation process will have to consider a 'worst case' scenario in order to gain regulatory approval whereby it is assumed that short term gas escape may occur.

Whilst the above uncertainties mean a risk based approach will be required to evaluate potential groundwater impacts from UCG, the proposed depth of UCG operations in the UK means that suitable site selection should allow operations to be carried out at an insignificant level of risk that is acceptable to the regulators. UK Coal Measures generally contain significant thicknesses of impermeable strata. If the site is located in geologically undisturbed areas where there are no realistically identifiable contaminant transport pathways, then it should be possible to demonstrate that contaminants are highly unlikely to be able to migrate to aquifers that can be considered as a 'water resource'.

It should be possible to gain a good level of information about underground conditions during the site investigation phase, but this will not provide a complete understanding. This report contains a framework for risk analysis that may be used as part of a suitable site selection and investigation process for UCG. By using this framework along with conservative contaminant transport modelling assumptions it should be possible to 'prove' there is a negligible risk of groundwater pollution. The analysis will have to account for potential permeability in coal seams, sandstone and limestones, as well as minor and major faults in the area. It will also have to allow for strata impacts associated with reactor caving and any nearby mining activities, as well as obvious man-made contaminant pathways such as abandoned wells or boreholes. Rules of thumb (such as ensuring development is more than 500m from existing workings) and conventional subsidence modelling theory are likely to be enough to evaluate the risk from mining activities and reactor caving, but more novel approaches are also discussed in Appendix F to this report if they are required.

Risk assessment will have to account for both the potential risk of short term gas losses during operations and longer term leachate issues. Gas transport is possibly the most problematic issue as the mechanisms for gas transport under pressure exceeding hydrostatic conditions is not well documented. However, conservative assumptions, sense checks and general guidance in

this report in the evaluation should enable assessors to provide a meaningful evaluation of the risk from gas escape.

As well as suitable site selection, there are a number of mitigation measures that can be adopted to help ensure that the risk of pollution is negligible. The main three are: using operational monitoring systems that can detect gas losses and ensure that reactor pressures are maintained below hydrostatic; ensuring that wells and boreholes used in the process are adequately sealed; and maintaining a 'cone of depression' in the groundwater around the reactor to ensure that aqueous phase contaminants flow towards the reactor where they can be pumped to surface and treated. Flushing and treatment of caved reactor water post operations may also help mitigation by removing contaminants, however until the leaching behaviour of contaminants within the pyrolysis zone is better understood then it is suggested that the value of this is uncertain.

Suitable groundwater monitoring will have to be adopted for any UCG process. The exact requirements for this cannot be determined in advance, however it is likely that monitoring will have to be geared towards proving that the conclusions of the risk assessment are valid and contaminants are not migrating beyond an area that is acceptable to the regulators.

10.2 SURFACE WATER

Surface water issues are reasonably conventional for UCG. Surface spillage and runoff risks are generally common to any industrial site involving the storage of chemicals, oils and polluted wastewaters. Discharge of treated wastewater is likely to require conventional licensing procedures and disposal methods. If wastewaters are produced as a condensate during the process, then they may be difficult to treat due to potentially high, fluctuating contaminant levels. However, the main risk from this is excessive cost or operational delays, which should be avoidable if suitable contingencies are in place.

10.3 CO₂ SEQUESTRATION

It is considered unlikely that sequestration in an exhausted gasifier could provide a secure long term repository for CO₂, although deep seams surrounded by impermeable strata may be the exception. Destressed coal seams over or underlying a gasified coal seam, appear to offer greater potential for safe sequestration of CO₂. Studies are currently being undertaken to determine the long term integrity of such reservoirs.

10.4 UK REGULATORY REGIME

Development of the trial site for UCG would need to be the subject of a planning application submitted in accordance with the Town and Country Planning Act 1990. In planning terms the trial is likely to be considered as a mining operation.

The semi-commercial operation would include electricity generation, which would be considered as an industrial process in planning terms, whilst the gasification phase would continue to be classed as a mining operation. If the capacity of the power plant exceeds 50 MWe it would be necessary to obtain consent from the Secretary of State for Trade and Industry under Section 36 of the Electricity Act 1989 and to submit a separate application under the Town and Country Planning Act 1990 for the mining operation. Whilst if the capacity does not exceed 50 MWe a planning application under the Town and Country Planning Act 1990 would be made to cover the two operations (mining and industrial).

The production of an EIA falls under Schedule 2 for both the trial or semi-commercial operation under the Planning EIA Regulations, but considering the characteristics of UCG and its potential environmental effects it is highly probable that a formal EIA would be required for both.

As UK legislation stands, both the trial and semi-commercial operation will fall under the Pollution Prevention and Control (England and Wales) Regulations 2000 as a Part A(1) Installation and the Pollution Prevention and Control (Scotland) Regulations 2000 as a Part A Installation. As such, the operator will need to have been issued with a permit to operate the installation(s). To issue a permit, the regulator will need to be convinced through the application process that the *best available techniques* (BAT) are to be used to minimise impacts of the installation(s) on the environment. The EU IPPC Directive contains a research and development (R&D) exemption clause that was not fully implemented in Great Britain. Consultation on the R&D exemption is currently being undertaken across Europe. If the PPC Regulations 2000 and the PPC Regulations (Scotland) 2000 were to be modified to implement the R&D exemption, then the trial might be exempt from the full requirements of IPPC.

The semi-commercial operation would also fall under the remit of the European Commission Directive on greenhouse gas emissions trading. If the semi-commercial operation includes gas reception facilities and the qualifying quantities of substances specified in the COMAH Regulations 1999 are exceeded at the site, then the gas reception facilities would fall under the COMAH Regulations.

It is anticipated that the drilling and exploration boreholes and the subsequent injection and production wells would require an Exploration Licence, an Operational Licence to work the coal and a leasehold interest in the coal from the Coal Authority. An Access Agreement from the Coal Authority may also be necessary to pass through other seams. In addition, a Surface Access Agreement would be required from the landowner and it would be necessary to sign the Interaction Agreement. It is currently uncertain as to whether a Petroleum Exploration and Development Licence would be required.

In relation to Health and Safety Regulations, there is uncertainty concerning the applicability of the Borehole Sites and Operations Regulations 1995 and the Offshore Installations and Wells (Design and Construction) Regulations 1996. However the Health and Safety Executive would expect the safety standards set by both of these Regulations to be met. The Offshore Safety Division of the Health and Safety Executive is the body with overall responsibility for ensuring compliance with the provisions of these Regulations and notifications under these Regulations constitute the principal documentation required by the Division.

10.5 AIR AND GLOBAL EMISSION ISSUES

Emissions to the atmosphere during the UCG trial will include oxides of nitrogen, hydrogen chloride and sulphur dioxide. The example design that was assessed used a minimum stack height of 13 m, and addressed the maximum gas production rate which will only occur for part of the nine month operational period. It was found that whilst modelled ground level concentrations of oxides of nitrogen and hydrogen chloride are well below the ambient air quality criteria, concentrations of sulphur dioxide concentrations substantially exceed the short term air quality criteria. The location of the maximum concentrations were found to be within the site boundary, assuming the plant were to be approximately centred within the site.

Substantial reductions in short term sulphur dioxide concentrations were found to result from doubling the stack height to 26 m. Any proposed trial design should be based upon a site specific dispersion modelling study incorporating a stack height sensitivity study. The site specific study should also evaluate the modelled results at the site boundary and at the nearest receptor. The findings should be considered in the light of current local air quality. It is unlikely that any sulphur dioxide abatement would comprise BAT for the trial plant, given the short term nature of the project. In those circumstances, a higher temporary stack would mitigate ground level concentrations, if acceptable on visual grounds. Where alternative sites with varying coal sulphur content are under consideration, the choice of a low sulphur bituminous coal for the trial would be advantageous in terms of air quality.

The dispersion model results for the semi-commercial plant operation incorporating removal of hydrogen sulphide were found to be a small fraction of the air quality objectives for all pollutants. This implies that there would be no particular constraints on coal sulphur content or any unusual stack height requirements, providing that the appropriate mitigation measures have been carried out. Nevertheless, as part of the supporting information for a planning application and an integral part of the IPPC application, a detailed site specific dispersion modelling study will be required.

The overall plant efficiency implications of the removal of CO₂ prior to power generation were briefly considered. Although the thermal efficiency appears

to be viable, it is questionable whether the additional capital cost of the plant would compare favourably with other power generation technologies such as gas-fired CCGT in the current energy market. However, in terms of minimising emissions of global warming gases, the technology appears to be advantageous in a future market driven by carbon emissions trading obligations.

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