An overview of the geological controls in underground coal gasification

Debadutta Mohanty

Non-Conventional Gases Section, CSIR-Central Institute of Mining and Fuel Research, Dhanbad 826 015, India

Email: drdmohanty@ymail.com

Abstract. Coal's reign will extend well into this millennium as the global demand for coal is expected to increase on average by 2·1% per year through 2019. Enhanced utilization of the domestic coal resource through clean coal technologies is necessary to meet the energy needs while achieving reduced emissions. Underground coal gasification (UCG) is one of such potential technologies. Geology of the area plays decisive role throughout the life of a UCG project and imperative for every phase of the project cycle starting from planning, site selection, design to cessation of operations and restoration of the site. Impermeable over/underlying strata with low porosity and less deformation are most suitable for UCG processes as they act as seal between the coal seam and the surrounding aquifers while limiting the degree of subsidence. Inrush of excess water into the gasification chamber reduces the efficacy of the process and may even quench the reactions in progress. Presence of fresh water aquifer in the vicinity of target coal seam should be abandoned in order to avoid groundwater contamination. UCG is not a proven technology that is still evolving and there are risks that need to be monitored and managed. Effective shutdown programme should intend at minimising the post-burn contaminant generation by flushing out potential organic and inorganic contaminants from the underground strata and treating contaminants, and to restore ground water quality to near baseline conditions.

1. Introduction

Coal is the major contributor to electricity generation holding a worldwide market share of 40 per cent being mainly driven by growing economies. The increasing contribution of renewable energy sources is not just sufficient to meet the ever increasing energy demands of the society and, coal and other fossil fuels will continue to be a major source of energy in the future. Coal's reign will extend well into this millennium as the global demand for coal is expected to increase on average by 2·1% per year through 2019 [1]. India is the world's third largest coal producer. The 2015 Indian coal inventory estimated, including only seams greater than 0.9 m in thickness and up to a depth of 1200 m, at 306.6 billion metric tons out of which less than 100 billion metric tons are recoverable by conventional mining methods. Besides hard coal, India is endowed with 44.1 billion metric tons of lignite resource. While India has vast coal resources, it also has huge petroleum and natural gas deficits. In such a scenario it is difficult to achieve the emission reduction targets from fossil fuels by using conventional coal-based technologies. Enhanced utilization of the domestic coal resource through clean coal technologies is necessary to achieve energy security while achieving reduced emissions (e.g. particulates, NO_x, SO_x and CO_2). Underground coal gasification (UCG) is one of such potential technologies to meet the future energy needs of coal-bearing countries worldwide in a cleaner manner

[2-4]. UCG technology can be used in India to produce clean energy using its domestic coal resources, including currently unmineable deposits, at competitive costs and with minimum damage to the environment. UCG is not a proven technology that is still evolving and there are risks that need to be monitored and managed.

About fifty UCG trials (Figure 1) were made in various countries including FSU, United States, Canada, Belgo-German, China, South Africa and Australia etc. most of which were short lived except Angren project of Uzbekistan which is operating over 50 years [5]. The trials in various countries, however, showed that UCG is highly adaptive to different conditions such as horizontal to steeply dipping coal seams of varying ranks, depths, geology and hydrogeological etc. New modern technologies with the upstream oil and gas industries along with century long trials provided further thrust to UCG to beyond the proof-of-concept phase to a phase of commercialization that is solely guided by the proper site characterization.

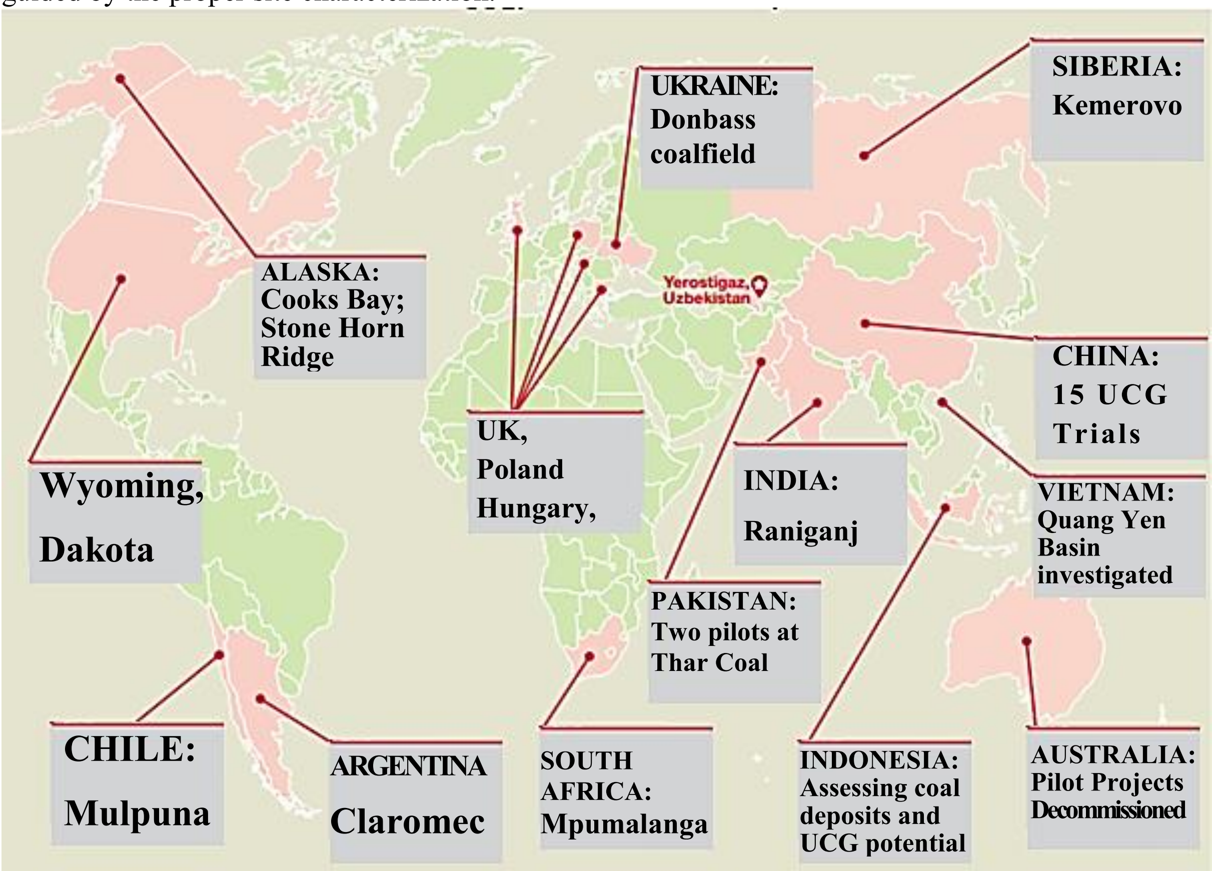


Figure 1. A brief snapshot of operational and prospective sites for UCG worldwide [6]

2. UCG Process

Underground Coal Gasification (UCG) is the process of in-situ gasification of coal aiming at recovery of heat value for power generation and, usable gaseous products as feed stocks for chemicals and fertilizers. The anticipated manifold increase in greenhouse gas emissions because of India's dependence on coal to meet the growing electricity demand may be mitigated economically by UCG combined with carbon capture and sequestration (CCS) than by addition of CCS to a coal-fired power plant. UCG also eliminates the hazards associated with conventional underground mining/surface strip mining or surface gasifiers operations. In contrast to conventional mining, UCG eliminates environmental issues of particular importance for utilization of low quality/high ash Indian coals as ash remains in the subsurface and needs no ash management, emits few black-carbon particulates, and it greatly reduces the need to mine and transport coal, since coal is used *in situ*. Overall, the Cfootprint and capital expense associated with UCG much less compared to coal mining, transport, and surface gasification.

The 3 zones (Figure 2) of UCG gasifier from ignition point farther are:

Zone-I: COMBUSTION ZONE $C + O_2 \rightarrow CO_2$

Zone-II: REDUCTION ZONE $C + CO_2 \rightarrow CO$

Zone-III: PYROLISIS ZONE Coal $\rightarrow$ Volatiles $\rightarrow CO, H_2, CH_4$

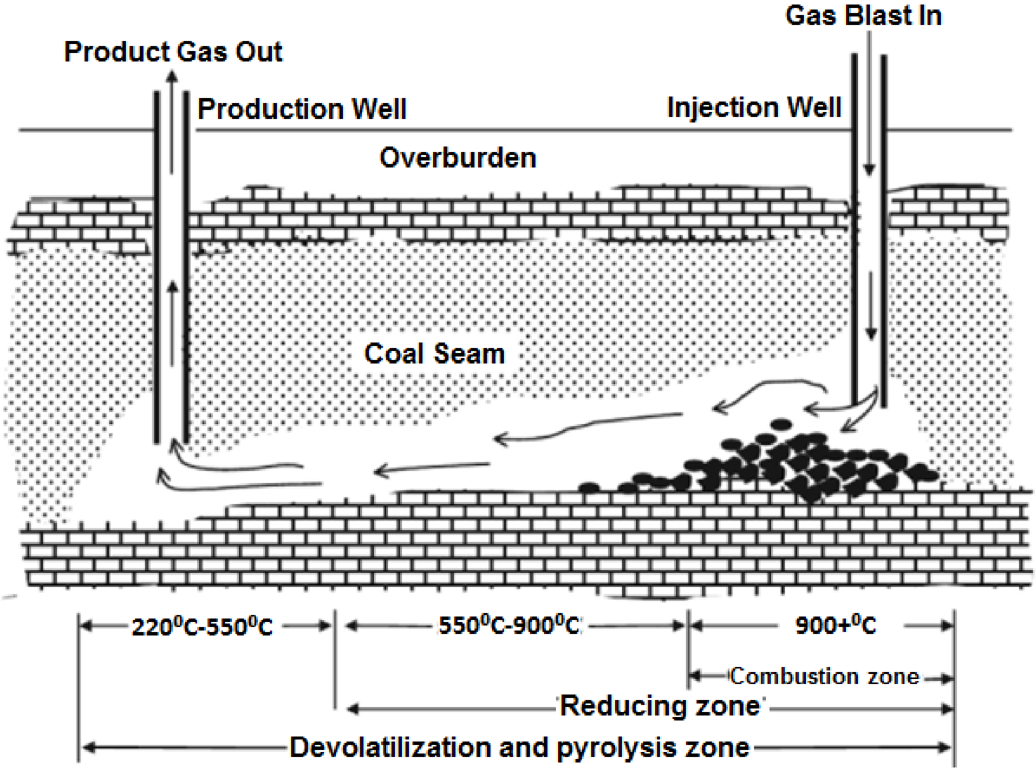


Figure 2. Schematic of in-situ gasification process [7]

3. Criteria for UCG site selection

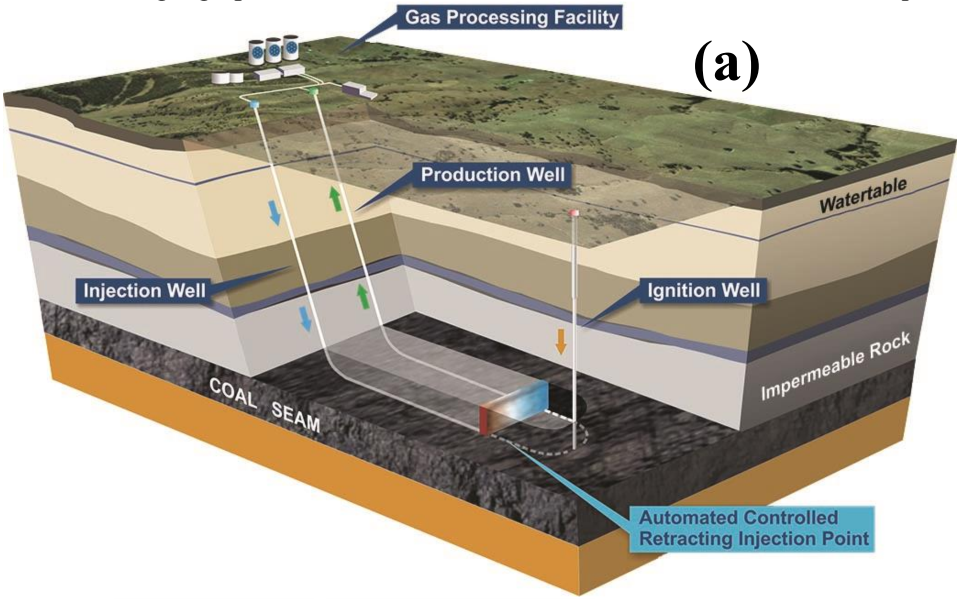
UCG is a highly efficient coal conversion process [8], with gasification efficiencies similar to that of surface gasifiers (75-85%) and mining efficiencies comparable with that of underground coal mining (around 60%). Not all UCG trials were successful. Some early trials even caused geoenvironmental damage e.g. Hoe Creek trials of US. The key learnings from the trails are:

- Proper site selection
- Choice of UCG reactor design best suited for the site (*e.g.,* Figure 3)
- Operation in accordance to strict guidelines
- Monitoring and mitigation of associated geoenvironmental risks

UCG is very much similar to surface gasification as far as the process is concerned. However, UCG is limited by the fact that it is site specific, in terms of geology and geography of the area unlike surface gasifiers that can be designed, regulated, maintained and monitored in planned manner. Predicting the strata behaviour, monitoring cavity growth and, predicting and maintaining product gas quality are greatly limited by the poor control and monitoring of such complex process that varies over space and time. Hence, geology of the area plays decisive role throughout the life of a UCG project and imperative for every phase of the project cycle starting from planning, site selection, design to cessation of operations and restoration of the site [9]. Thus the criteria for UCG site selection are:

- Suitable coal seam characteristics for favourable operational conditions,

- Suitable geological and hydrogeological characteristics with negligible risk of groundwater pollution from the UCG operation, and
- Suitable geographic location that satisfies various surface installation requirements for operation.



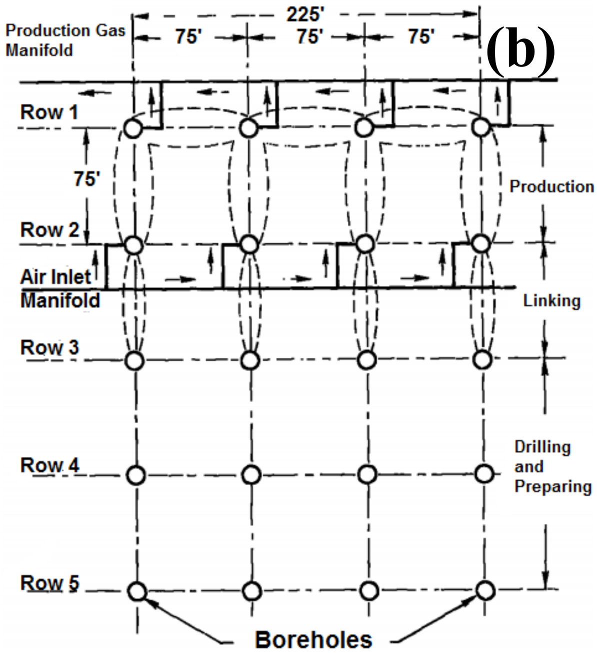


Figure 3: a. Carbon Energy's approach to UCG [10] b. plan view of a typical Soviet UCG process adapted for horizontal seams [11].

Understanding geology of the area provides necessary safeguards for protecting the environment. Geologically isolated deep beds are preferred to reduce the surface expressions of subsidence due to UCG cavity growth. Aquifers should be avoided in the vicinity of the UCG site. If at all this should be deep and consists of saline/non-potable water with stratigraphic seals. Structural integrity of overburden and coal should be insured to avoid possibility of gasifier roof caving in.

3.1. Coal seam geology

Coal deposits of different regions around the world differ remarkably in their geological setting, posing challenges for determination of selection criteria for a potential UCG sites. These factors include coal seam geology; physical, chemical and petrographic properties of coal; geomechanical properties of coal and surrounding rocks; and geo-hydrological regime of the area. Various geological (isopach/structure contour/isorank) maps, litholog, well log, seismic data etc. along with their spatio-temporal analysis and correlation (Figure 4) are useful for assessment and planning of UCG projects.

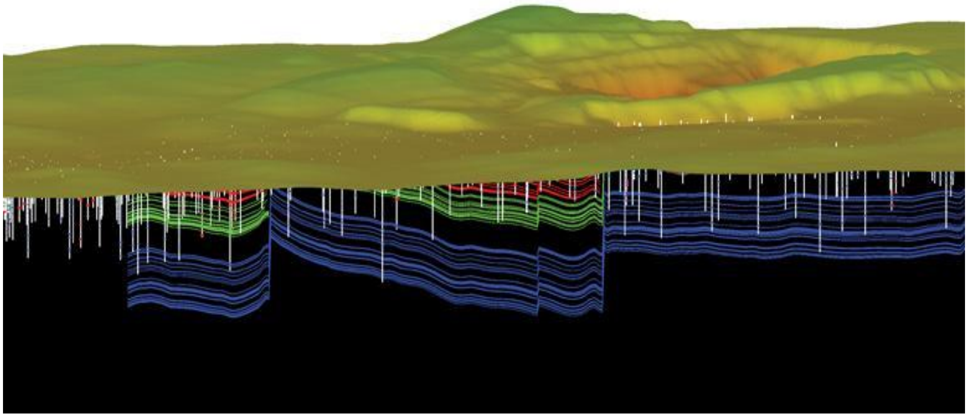


Figure 4: Showing subsurface geological modelling using various geological and geophysical data (from http://www.srk.com/)

Higher pressure in underground gasification chamber assures no groundwater inflow to the cavity. However, as pressure increases with depth of seam, deep seams with high coal and overburden permeability pose problem of enhanced product gas loss to the surrounding aquifer thereby altering the chemistry and contaminating the groundwater. An impermeable overburden helps provide a reasonable balance between pressure and gas losses.

3.2. Coal properties

Coal is a heterogeneous mixture of organic (macerals) and inorganic (minerals), and it is from the organic component that syngas is generated during gasification. The inorganic component has a significant impact on gasifier performance, where certain minerals can act as catalysts, others as inhibitors, depending on the gasification condition and type of mineral. Gasification of coal occurs in two stages, namely: (1) rapid pyrolysis devolatilizing the coal leading to char formation, and (2) char reaction. Reactivity in this context is the rate at which char will react with steam/oxidant to convert into syngas. Reactivity depends on chemical and physical (porosity) structure of char, and catalysts. Reactions occur only on the reactive surface area, and not all micropores may be reactive. If the heating rate is slow, devolatilization is followed by gasification; if the heating rate is fast, the two processes may occur simultaneously. Though all coal types of different ranks can be extracted and exploited through UCG process, low rank lignite and sub-bituminous are preferred for UCG being more permeable and reactive to gasification process. Some low coals shrink upon heating making the connection between the injections well and production well even greater. Higher ash content reduces gasifier efficiency due to heat loss and high O_2 demand. Leachability study of ash/slag is essential for disposal and environmental reasons.

Coal has dual porosity i.e., matrix/inherent (macro, meso, micro- pores) porosity and induced (cleat) porosity. The structural heterogeneity is the result of changes to the original organic matter due to varying PT conditions during the geological history. UCG depends on the porosity and permeability of the coal seam. Permeability is important in linking of injection and production well; better cleated and more permeable coal seams have greater ability to transport gases during gasification process while more porosity provide larger surface area for reactions to proceed effectively. Low rank coal are characterised by having porous and permeable structure.

3.3. Geological and hydrological conditions

The geological and geotechnical properties of surrounding strata as well as the coal seams have a direct bearing on the UCG process. Impermeable over/underlying strata with low porosity and less deformation are most suitable for UCG processes as they act as seal between the coal seam and the surrounding aquifers while limiting the degree of subsidence. Hydrological regime of the area forms an important screening criterion of potential UCG site. Water is needed for the UCG process as it takes part in the gasification reaction to add value to syngas composition. However inrush of excess water into the gasification chamber reduces the efficacy of the process and may even quench the reactions in progress. Presence of fresh water aquifer in the vicinity of target coal seam should be abandoned in order to avoid groundwater contamination. Risk of groundwater contamination arises mainly due to hot product gases escaping through crack and fissures while gasification operation is active. Contamination may also be caused due to post-burn leaching when gasification cavity fills with water. The case may be more devastating when the gasification chamber collapses thereby directly connecting coal to the aquifer. Hence coal seam suitable for a successful UCG process should preferably be in a vertical separation of more than 100m from the major aquifer.

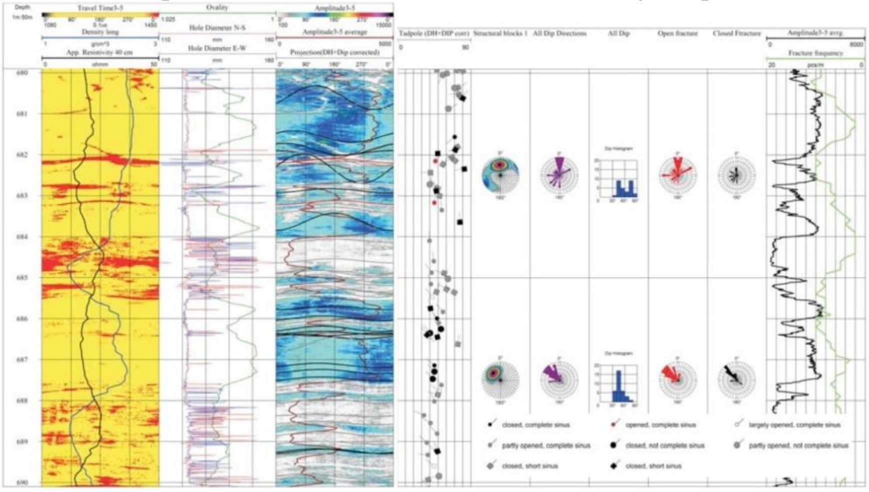


Figure 5. Acoustic Borehole Televiewer data showing borehole gauge, ovality, dip of drilling and its direction, attitude of fractures and fissures etc. (from [12])

4. Techniques used for UCG site investigation

UCG site selection requires proper assessment of depositional setting, tectonic/structural framework, hydrodynamics and coal type of the basin under consideration [13]. For this detailed geological information should be collected from various source. The detailed exploration programme includes literature information, outcrop mapping, borehole lithology, seismic survey, well log data etc. Subsurface geology is investigated with the help of borehole correlation. The borehole lithologs are supplemented with various downhole well log data. Coal seam geometry (mapping), petrophysical evaluation of coal and surrounding rock, geomechanical parameters, cleat/fracture system characterisation, structural analysis etc. are some of the prime objective of down-hole geophysical investigations. Various well logging techniques deployed now-a-days are outlined below:

- Resitivity/SP logs: To demonstrate occurrence of sand with water and clay bands based on formation resistivity
- Gamma-Gamma log: To evaluate formation density
- Gamma Ray log: To detect clay/mudrock layers using natural radioactivity
- Neutron log: To determine porosity
- BHTV (Borehole Televiewer): To locate fractures and determine hole condition (Figure 5)
- OPTV (optical imagery): To monitor borehole walls

Table 1. Some of the instrumental techniques used for coal/rock characterization

Generic Name	Usage
CHNS analyzer	Chemical Characterization
Petrological microscope	Maceral/Reflectance

Generic Name	Usage
Proximate Analyser	Chemical Characterization
BET surface area analyzer	Surface characterization
Ultra pycnometer – 1000	Porosity study
Mercury porosimete	Porosity study
CPT/IPT Apparatus	Crossing Point and Ignition Point measurements
XRD	Mineralogical Study
FE-SEM EDAX	Morphological/Mineralogical Study
Uniaxial compressive strength Testing Facility	Physico-Mechanical Study
Triaxial strength Testing Facility	Physico-Mechanical Study

Locating faults, defining lateral extent and nature of strata at the site needs critical desk study of the available data that may include *in situ* hydrogeological data and detailed seismic data along with borehole litholog and well log data. On site hydrological investigation includes [14] borehole water pressure and its deviation from hydrostatic head, transmisivity and water quality (mainly total dissolved solids/conductivity). Different instrumental techniques used for coal/rock characterization are as given in Table 1.

5. Monitoring UCG process

UCG monitoring was initially carried out during the 1930's in the former Soviet Union (FSU) with thermocouples, flow rate meters and gas analysis equipment. Efficient and safe operation of UCG requires strategic UCG monitoring program which includes the followings:

- Process parameters such as gas flow rates both for oxidant injection and syngas production, temperature, pressure and syngas content;
- Geomechanical parameters such as alteration in stress regime through coal seam, overburden and cavity pressures, cavity development, subsidence and ground deformation etc.; and
- Environmental parameters such as change in water table, groundwater chemistry and ambient air quality etc.

The strategic UCG monitoring program should be done in three stages:

- *Assessment and Planning*: During this phase, the site is characterized geographically and geologically. Based on these studies, an array can be designed to meet the requirements of regulators and other stakeholders.
- *Baseline Monitoring*: Reliable pre-burn baseline surveys must be carried out before hand to understand the background values and to provide a basis for difference mapping.
- *Operational Monitoring*: Regular and frequent sampling during the burn for near real-time monitoring of injection/production wells to look for circulation behind casing, failures within the well bore and, to observe ground deformation, ground water contamination and other operational problems or failures.
- *Array Monitoring During and After Gasification*: Long-term post-burn monitoring phase involves active surface and subsurface arrays, with the option for additional tools around high-risk zones. The recurrence and total duration of monitoring is to be determined by the research goals, the site parameters, the budgetary status and regulatory needs.

Monitoring program requires appropriate sensors for comprehensive spatial as well as temporal coverage of an entire UCG process. Lateral and vertical network of near, middle and far monitoring wells are required to collect data and samples from the coal seam, overburden and underburden. Apart from routine monitoring instrumentation, modern technologies are available those can be easily be deployed to generate high density 2D/3D data e.g., electromagnetic imaging, resistance tomography, seismic and magnetotelluric techniques can be used for detection of burn front and delineation of cavity growth [15]. Extensometers, shear strips and piezometers are generally used to monitor surface deformation. New techniques such as tilt meter and InSAR are now-a-days available for monitoring deformation and subsidence, and fiber optic temperature sensors for monitoring cavity temperature.

Cavity growth due to *in situ* gasification often leads to roof collapse leading to subsidence and establishing connection between the UCG cavities with overlying aquifers. An active groundwater monitoring program is required to address the concerns of groundwater contamination during UCG operation [16]. Borehole hydrological monitoring, geochemical and tracer techniques, geophysical monitoring (seismic, electric, magnetic and gravity) methods should be variously deployed for monitoring the operation, shut down and restoration. Latest in the sequence the ambient air quality monitoring for UCG is required to identify potential pollutants escaped from the gasifier.

6. Shutting down

Appropriate shutdown procedure is highly imperative to avoid issues of possible contamination as pyrolysis products will no longer be consumed on cessation of reaction following non-injection of oxidants. Effective shutdown programme should intend at minimising the post-burn contaminant generation from pyrolysis products by accelerating the cooling of the cavities and preventing post gasification pressure build up. This may be achieved by pumping out water from the cavities to maintain hydrostatic gradient towards the reactor to flush out potential organic and inorganic contaminants from the underground strata and treating contaminants, and to restore ground water quality to near baseline conditions.

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Acknowledgement

The author is grateful to CSIR Network Project CoalGasUrja (ESC-0302) for financial support. He also thanks Dr. Pradeep K Singh, Director, CSIR-CIMFR, for his support and guidance in preparation of this paper.