

Review

# Contamination of groundwater due to underground coal gasification

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Underground coal gasification (UCG) generates potential groundwater pollution because it changes local hydrogeological parameters. Groundwater pollution is caused by diffusion and penetration of contaminants generated by UCG processes towards surrounding strata and possible leaching of residue by natural groundwater flow after gasification. A large number of hazardous water-borne contaminants were identified during different UCG operations conducted so far, and in some locations long-term groundwater contaminations were observed. Organic pollutants were detected after UCG process are phenols, benzene with its derivatives, polycyclic aromatic hydrocarbons (PAHs), heterocycles etc. and inorganic pollutants includes ammonia, mercury, zinc, sulphates, cyanides, heavy metals etc. Adsorption function of coal and surrounding strata makes a significant contribution to decrease the contaminants over time and distance from the burn cavity. Possible pollution control measures regarding UCG include identifying unsuitable zone, sitting a hydraulic barrier and pumping contaminated water out for surface disposal. The paper enumerates major pollutants identified in different UCG sites and its mitigation measures during gasification processes, and groundwater remediation after gasification.

**Key words:** Underground coal gasification, groundwater contamination, water influx.

## INTRODUCTION

Underground coal gasification (UCG) is a procedure for extracting the synthesis gas (syngas) from *in-situ* underground coal seams that could not be economically extracted by conventional mining methods. UCG process produces gas suitable for high-efficiency power generation, chemical feedstock, fuel etc. The first available environmental data on UCG came from later United States trials, mainly regarding the Hanna and Hoe Creek UCG trails (Cooke and Oliver, 1983), at this site

groundwater contamination monitoring was conducted pre- and post-UCG process. The results showed that UCG at shallow depths can pose a significant risk to groundwater in adjacent strata. UCG process, involves air/oxygen and steam pumped into the underground coal seam through an injection well. The introduction of an oxidizing gas produces heat, which partially combusts the coal *in-situ* and creates the syngas product, primarily composed of hydrogen (H<sub>2</sub>), carbon monoxide (CO),

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carbon dioxide (CO<sub>2</sub>) and methane (CH<sub>4</sub>) (Stephens et al., 1985). The syngas is extracted from the UCG burn cavity by a production well, which brings the gas product to the surface for industrial uses. A schematic diagram of UCG process is shown in Figure 1. UCG is partly environmental friendly due to non-discharge of tailing, decrease of sulfur emission, and non-discharge of ash, mercury and tar. In UCG process, physico-chemical interaction changes natural stress in the surrounding rock mass, which influences contaminants formation in the UCG reactor as well as inducing potential subsidence, and pollution of groundwater, surface water and atmospheric quality. Subsidence creates a hazard for any surface infrastructure that presents above the UCG zone and may create detrimental changes in surface or groundwater hydrology above the cavity (Torres et al., 2014). UCG cavity is a source of both gaseous and liquid pollutants. The risk of groundwater pollution from UCG depends on whether the contaminants can migrate beyond the immediate reaction zone to more sensitive groundwater areas. Transport of aqueous phase contaminants depends on permeability of *in-situ* rocks, geological setting of gasification reactor and hydrogeology of the adjacent area.

For the commercialization of UCG technology environmental impact studies, especially of groundwater pollution prevention and control is necessary. The paper identifies possibility of underground water pollution due to UCG and analyzes the fate of contaminants (organic and inorganic) as well as formulates strategies for groundwater pollution control.

## GROUNDWATER CONTAMINATION BY UNDERGROUND COAL GASIFICATION

Contamination of ground water is considered as a serious environmental threat. Degradation of ground water can result from any of the following three sources (Ahern and Frazier, 1982):

- (i) Organic contaminants in tars produced during carbonization or gasification;
- (ii) Inorganic salts or trace elements in the leachate from the ash; and
- (iii) Changes in flow patterns or rates resulting from subsidence or interconnection of aquifers by fracturing.

Groundwater contamination around UCG reactor is caused by dispersion and penetration of pyrolysis products of coal with migration of groundwater and escaped gases. During the gasification process, air or oxygen is injected with high pressure equal to or greater than the surroundings hydrostatic pressure ( $P_h$ ). Some of the gas products are therefore lost to the surrounding permeable media and overlying strata, as a result of cracks in the overburden, as shown in Figure 2. In UCG

reactor temperature is very high and due to this, solvent power of water increases, and density and viscosity of water decreases. After gasification coal ash is left in cavity and due to low pressure of reactor groundwater begins to enter into the gasifier. It may contain some higher molecular weight organic substances that are produced during pyrolysis of coal seam. The more volatile the product, the farther it is transported out into the surrounding coal strata before condensing or dissolving in groundwater. As the cavity cools and fills with water, the residual ash is leached, leading to increase in pH and in the concentration of many inorganic species. During this period, thermally driven convection currents transport some of the non-volatile inorganic contaminants from the ash into the surrounding formation. After that the concentrations of many contaminants will continue to change as a result of adsorption on the coal and strata or reactions among different species.

Due to hydraulic gradients, migration of groundwater will occur through coal seams and burned out areas which lie below the water table. This may cause soluble components sorb on ash or char to be leached out and transported away from the gasification site. An increase in dissolved organic material could result from partial dissolution of coal tars formed during gasification (Phillips and Muela, 1977).

Subsidence of the overburden above the UCG burn cavity also can cause groundwater contamination problems. An example of this phenomenon was found at the Hoe Creek UCG test site in the United States where aquifers cross connection occurred during gasification operations. The problem was transmission of pollutants generated in the burn zone through fractures caused by subsiding overburden into overlying aquifers. However, this should be avoided during the phase of choosing the study site (Burton et al., 2004). Initially at the time of gasification when the temperature of the gasification cavity is high, most of the returning water is vaporized and may be vented to the surface via the processing wells.

## WATER INFLUX DURING UNDERGROUND COAL GASIFICATION PROCESS

Groundwater plays an important role in gas formation process during UCG. The major sources of water in the cavity areas are as follows:

- (i) Water already available in the coal;
- (ii) Water influx by permeable coal beds: It is the major source of water influx into the cavity; and
- (iii) Water influx by overburden: It is the second major source of water into the cavity. Water influx by overburden is mainly two types, firstly when UCG process starts, water influx happen due to permeability of

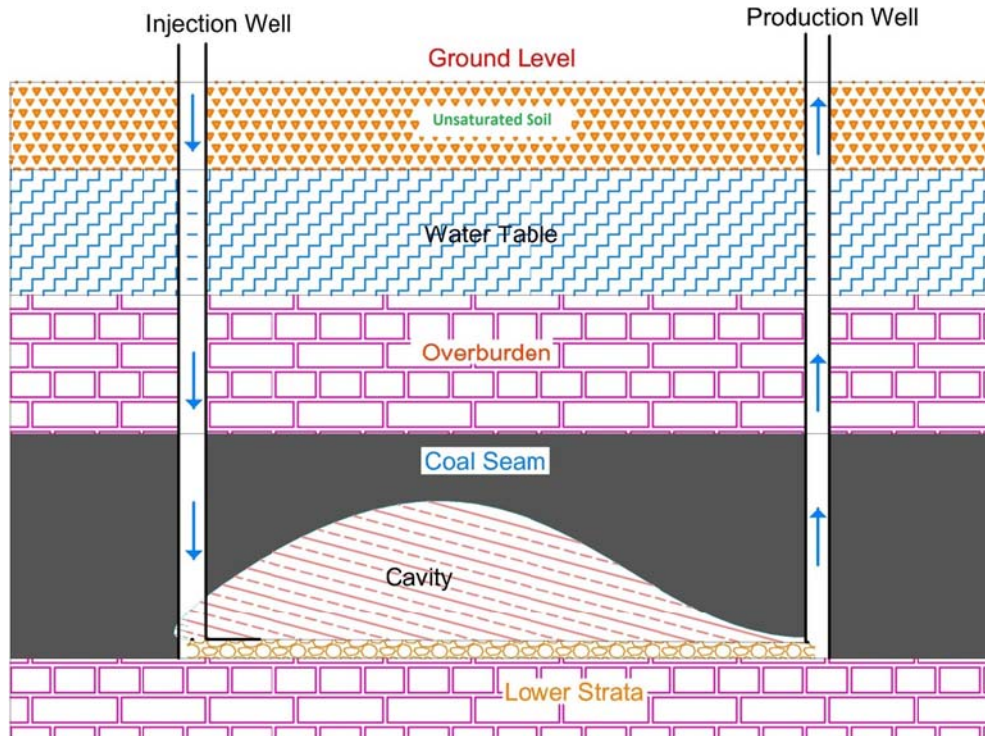


Figure 1. Schematic diagram of UCG process.

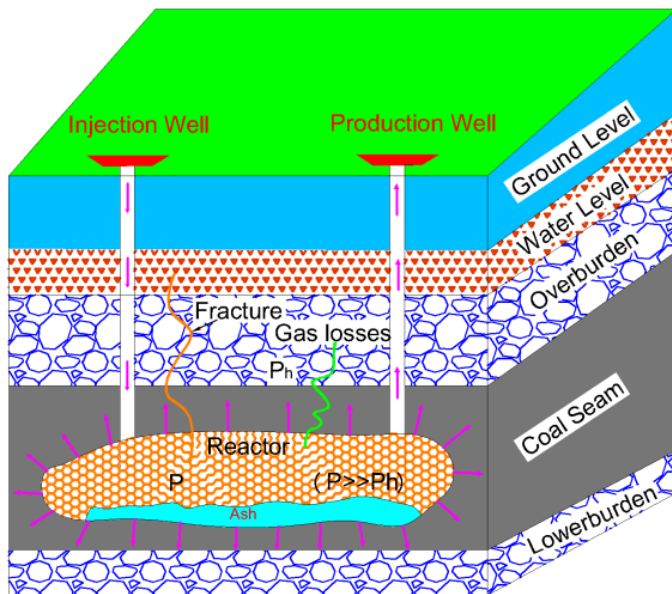


Figure 2. Fracture developed due to collapse of strata and gas escaped from the fracture.

rock overburden as shown in Figure 3, and secondly as coal burns away during UCG and overburden is exposed to intense heating. This causes extensive spalling of rock as it dries. Rock is exposed to thermal stresses and steam pressure (Sury et al., 2004).

Role of water in UCG process depends on whether the water influx is into the hot UCG cavity or downstream into the carbonized link zone. Water influx into the cavity can participate in gasification reaction and downstream into the carbonized link can participate directly in water-gas shift reaction which exchanges carbon monoxide for hydrogen, and indirectly in the methanation reaction; furthermore, it cools the product gas and thus decreases the potential for surface heat exchange to recover the sensible heat of the product gas but, at the same time, reduces high temperature corrosion of the production well and surface piping system. The amount of water flowing in is measured and controlled by the ratio of water to gasified coal (W/W). When the water influx ratio is higher than 0.5, a normal gasification process ceases at temperatures below 800°C. Therefore, a controlled groundwater influx is very important for enhanced-hydrogen gas preparation in UCG field tests by using the stored heat energy underground (Shu-qin et al., 2008).

### Important reactions of underground coal gasification

The controlled gasification of UCG process involves burning of coal with air or other oxidants with complex series of reactions including carbonization, distillation, oxidation, reduction, pyrolysis, water-gas shift conversion, water-gas reaction, methanation and Boudouard reactions (Haider, 2012). The followings are

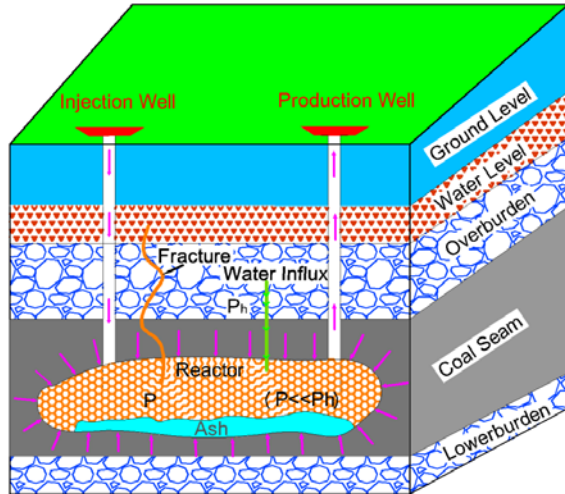


Figure 3. Water influx into the burned cavity.

significant reactions involved during UCG process:

- (i) Oxidation reaction:  $C + O_2 \rightarrow CO_2 + 393.8 \text{ MJ/kmol}$
- (ii) Partial oxidation:  $2C + O_2 \rightarrow 2CO + 231.4 \text{ MJ/kmol}$
- (iii) Oxidation:  $2CO + O_2 \rightarrow 2CO_2 + 571.2 \text{ MJ/kmol}$
- (iv) Reduction/ Boudouard reaction:  $C + CO_2 \rightarrow 2CO - 162.4 \text{ MJ/kmol}$
- (v) Hydrogenous water-gas reaction:  $C + H_2O (g) \rightarrow CO + H_2 - 131.5 \text{ MJ/kmol}$
- (vi) Shift conversion:  $CO + H_2O \rightarrow CO_2 + H_2 + 42.3 \text{ kJ/mol}$
- (vii) Methanation:  $CO + 3H_2 \rightarrow CH_4 + H_2O + 206.0 \text{ kJ/mol}$
- (viii) Hydrogenation gasification:  $C + 2H_2 \rightarrow CH_4 + 87.5 \text{ kJ/mol}$

**Effect of aquifer interconnection**

Aquifer interconnection due to UCG process is investigated in Hoe Creek II and Hoe Creek III experiment in Wyoming (Stone et al., 1982). Aquifer interconnection would be happened when two coal seams are gasified in a column and a strata lies between them. After gasification of both coal seams (gasification process started at first lower coal seam) and the strata may be collapsed, depending on the strata strain and aquifers interconnect to each other. So, due to aquifer interconnection possibilities of groundwater contamination increases.

**GOVERNING EQUATION OF GROUNDWATER FLOW AND TRANSPORT**

**Ground water flow equation**

The two-dimensional equation of continuity for flow in one aquifer to multi-aquifer systems is represented by the

following equation (Contractor and Shreiber, 1987):

$$\frac{\partial}{\partial x}(K_x B_I \frac{\partial}{\partial x}(h_I)) + \frac{\partial}{\partial y}(K_y B_I \frac{\partial}{\partial y}(h_I)) + r + Q_I + \frac{K_{Ia}}{B_{Ia}} (h_{I-1} - h_I) + \frac{K_{Ib}}{B_{Ib}} (h_{I+1} - h_I) = S_I \frac{\partial}{\partial t}(h_I) \tag{1}$$

Where,  $K_x, K_y$  are the permeabilities in  $x, y$  directions,  $h_{I-1}, h_I, h_{I+1}$  are piezometric heads in Aquifers I-1, I, I+1;  $B_I$  is the saturated thickness of Aquifer I;  $r$  is the recharge into the aquifer;  $Q_I$  is the pumping rate from aquifer I;  $K_{Ia}, K_{Ib}$  are the permeabilities of aquitards above and below aquifer I;  $B_{Ia}, B_{Ib}$  are the saturated thicknesses of aquitards above and below aquifer I; and  $S_I$  is the storage coefficient of aquifer I. For derivation of equation some essential assumptions has taken into consideration, such as water is homogeneous with constant density, Darcy's law is valid, the Dupuit approximation is assumed to be valid, one dimensional vertical flow is assumed to occur in the aquitards without storativity effects, the off-diagonal terms of the conductivity tensor ( $K_{xy}, K_{yx}$ ) are equal to zero; and  $x$  and  $y$  being the principal axes.

**Water quality model**

Two-dimensional equation for mass transport is described below:

$$\frac{\partial}{\partial t}(RC) = \frac{\partial}{\partial x}(D_{xx} \frac{\partial C}{\partial x} + D_{xy} \frac{\partial C}{\partial y} - V_x C) + \frac{\partial}{\partial y}(D_{yx} \frac{\partial C}{\partial x} + D_{yy} \frac{\partial C}{\partial y} - V_y C) + \mu C + \gamma + \sum \eta C + F_{I-1} + F_{I+1} \tag{2}$$

Where,  $C$  is concentration;  $R$  is the retardation factor;  $D_{xx}, D_{xy}, D_{yx}, D_{yy}$  are dispersion coefficients;  $V_x, V_y$  are seepage velocity components in  $x, y$  direction;  $\mu$  is decay coefficient;  $\gamma$  is the recharge parameter;  $\sum \eta C$  is the effect of pumping summed over the number of wells,  $\eta$  being the discharge constant;  $F_{I-1}$  is the interaction effect with the aquifer above I;  $F_{I+1}$  is the interaction effect with the aquifer below I.

Now,  $F_{I-1}$  = interaction of aquifer I with aquifer I-1 above it.

$$F_{I-1} = \begin{cases} \frac{K_{Ia}}{n_I B_I} \frac{h_{I-1} - h_I}{B_{Ia}} C_{I-1}, & \text{if } h_{I-1} > h_I \\ \frac{K_{Ia}}{n_I B_I} \frac{h_I - h_{I-1}}{B_{Ia}} C_I, & \text{if } h_{I-1} < h_I \end{cases}$$

Where  $n_I$  is the effective porosity of aquifer I and  $F_{I+1}$  = interaction of aquifer I with aquifer I+1 below it.

$$F_{I+1} = \begin{cases} \frac{K_{Ib}}{n_I B_I} \frac{h_{I+1} - h_I}{B_{Ia}} C_{I-1}, & \text{if } h_{I+1} > h_I \\ \frac{K_{Ib}}{n_I B_I} \frac{h_I - h_{I+1}}{B_{Ia}} C_I, & \text{if } h_{I+1} < h_I \end{cases}$$

The dispersion coefficients are related to the velocity of ground water flow and to the nature of the aquifer using

Scheidegger's equation.

$$D_{ij} = \alpha_{ijmn} \frac{V_m V_n}{V} \quad (3)$$

Where,  $\alpha_{ijmn}$  = the dispersivity of the aquifer (dimensions of length),  $V_m, V_n$  = components of velocity in m, n direction, respectively,  $V$  = the magnitude of the velocity.

$$= [(V_m)^2 + (V_n)^2]^{1/2}$$

An isotropic aquifer dispersivity tensor defined in terms of two constants. These are the longitudinal and transverse dispersivities of the aquifer ( $\alpha_L$  and  $\alpha_T$ , respectively). These are related to longitudinal and transverse dispersion coefficients by:

$$D_L = \alpha_L V \text{ and } D_T = \alpha_T V$$

After expanding Equation (3) and substituting Scheidegger's identities, the components of the dispersion coefficient for two-dimensional flow in an isotropic aquifer are:

$$\begin{aligned} D_{XX} &= D_L \frac{(v_x)^2}{V^2} + D_T \frac{(v_y)^2}{V^2} \\ D_{yy} &= D_T \frac{(v_x)^2}{V^2} + D_L \frac{(v_y)^2}{V^2} \\ D_{xy} &= D_{yx} = (D_L - D_T) \frac{v_x v_y}{V^2} \end{aligned}$$

These essential assumptions were made in the derivation of equation are that the solute moves in a saturated, medium is porous, the solute concentration does not affect the density and viscosity of the water in the aquifer, and the dispersion coefficients are assumed to be proportional to the velocity, hence can vary with time from node to node.

## TYPES OF GROUNDWATER CONTAMINANT

### Organic contaminants

In laboratory and field studies, it has been observed that sorption of contaminants on aquifer substrate is an important mechanism that acts to decrease the concentration of contaminants in groundwater over time. However, certain contaminants are not sorbed sufficiently to alleviate concern for their transport in groundwater aquifers. The results (laboratory and field studies) specify that after a time period organic contaminants concentration are decreased and composition are changed. Phenols and low molecular weight aromatic hydrocarbons persist in solution while less soluble components such as three, four, and five-ring aromatic hydrocarbons are removed by sorption (Stuermer et al., 1982). The major organic groundwater contamination

identified as phenols. Phenol is a constituent whose maximum concentration has varied from site to site. Maximum concentration is reported from range of 20 to 450 mg/L in six sites. Other organic pollutants were benzene, naphthalene, toluene, xylene, Dissolved Organic Compound (DOC), Polycyclic Aromatic Hydrocarbons (PAHs) as summarized in Table 1. According to data reported from six sites benzene is another organic substance of particular concern for its concentrations occurring at many of the sites and its designation as a human carcinogen. But benzene contamination is generally confined to within 9 m of the gasification cavities in the affected aquifers. As expected, volatile organics in the process tar and water, alone, showed the presence of over 250 different organic components (Campbell et al., 1979). The organic materials present in the groundwater were analyzed by two different procedures. In one procedure the dissolved organic carbon was fractionated into two broad groupings of hydrophilic and hydrophobic species. Each of these was then further fractionated into groups of acidic, basic and neutral compounds. In second procedure gas chromatography- mass spectroscopy (GC-MS) analysis was used to identify and quantify the concentrations of many of the individual organic compounds present (Campbell et al., 1979).

So, based on general solubility characteristics of these potential water pollutants, phenols pose the greatest threat, while pyridines and anilines are also regarded as soluble and therefore likely to be present in the water. Quinolones, which are somewhat less soluble, may be present at trace levels. Aromatic hydrocarbons are not expected to present a significant hazard to water quality (Phillips and Muela, 1977).

The post-gasification distribution of phenolic materials is a function of distance from burn cavity and time. Inside the burn cavity zone, phenolic concentration is found low due to strong adsorption and hence retardation in movement of aqueous phenol through a sub-bituminous coal bed (Wang, 1979). Organic pollutants found in UCG process are volatile and non-volatile. Volatile aromatic materials are benzene, toluene, xylenes and naphthalene. The more volatile (lower-molecular weight) are transported farther from the burn boundary. The groundwater from several wells of Hoe Creek I sampled after gasification was analyzed using GC-MS.

### Inorganic contaminants

Coal is primarily consists of organic materials such as carbon, hydrogen, oxygen, nitrogen and sulfur. Inorganic material present is due to layers of clay, carbonate or mineral matter such as pyrite which are washed into the swamps along with plant material during initial stages of coalification. After combustion of coal, inorganic material is found mainly to be associated with ash, which can



**Table 1.** Baseline and maximum reported organic contaminates concentrations in six sites (Ahern and Frazier, 1982).

Organic constituents	Hoe Creek I		Hoe Creek II		Hanna I		Hanna II		Fairfield		Tenn. Colony	
	Base	Max.	Base	Max.	Base	Max.	Base	Max.	Base	Max.	Base	Max.
Phenols(mg/L)	0.001	450	-	45	45	-	-	270	0.1	20	0.005	100
Benzene (µg/L)	4	192	-	-	-	-	-	607	-	-	-	-
Naphthalene (µg/L)	5	0	-	-	-	-	-	640	-	-	-	-
Toluene (µg/L)	11	68	-	-	-	-	-	2200	-	-	-	-
Xylene (µg/L)	1	10	-	-	-	-	-	1000	-	-	-	-
DOC (mg/L)	4	230	-	-	-	-	-	-	-	-	2.5	790

comprise from 3 to 20% of the original coal volume (Lang, 1982). Ash in the burn cavity was identified as a source of most of the inorganic constituents which moved with groundwater after gasification. Calcium, sulfate and hydroxide were the major inorganics leached out of ash. Hydroxide concentrations were lower in leachate from lignite ash than from bituminous and subbituminous ash (Humenick and Lang, 1980). Volatile inorganic species exhibit increasing concentration during UCG due to movement of volatile species out of the burn cavity. Ammonia produced during pyrolysis are detected at high concentrations in surrounding strata.

Several studies have identified changes in inorganic substances in groundwater due to the gasification process. Table 2 provides data for Tennessee Colony site in Texas which are representative of increase in inorganic groundwater constituents at other UCG sites. Soluble ash components are seen to increase total dissolved solid (TDS) concentrations in cavity water (Table 3). The materials include a wide array of ionic species, mainly calcium, sodium, sulphate and bicarbonate. There are, however, many other inorganic substances leached into the groundwater which are of interest, even though

they are present in smaller amounts. These include calcium, aluminum, mercury, magnesium, sulphate, manganese, ammonia, arsenic, boron, iron, zinc, selenium, hydroxide and some radioactive materials such as uranium (Ahern and Frazier, 1982).

Field data and laboratory ash leaching experiments indicate that inorganic contaminates tend to increase due to ash leaching. Different results at different sites are probably due to coal and ash composition, gasifier temperatures, sampling techniques and natural water quality. Only one parameter, pH showed very large variations among investigators. Ash from Texas lignite showed little change in pH. Again, these differences could be accounted for by the inherent differences between coal and lignite, or may be site specific. Other groundwater contaminant grows during UCG process are total dissolved solids (TDS) and pH in different UCG sites (Table 3).

#### Surface water contaminations

Syngas produced by UCG contains a component of liquid or vaporized water which is removed from

gas before the gas is used for power generation and chemical feedstock. This water contains residual hydrocarbons, benzenes, phenols and polycyclic aromatic hydrocarbons (PAHs) which are fully treatable. Potential pollution of surface water in UCG is extremely low, and the common pollutants are phenols, ammonia, chemical oxygen demand (COD), pH, conductivity and sulphides (Sury et al., 2004). The surface water can be affected by groundwater pumping and drilling operations, but the water pumped out to the surface may contain phenol (Green, 1999).

## MIGRATION OF GROUNDWATER CONTAMINANTS

### Migration with natural groundwater flow

Groundwater pollution due to UCG is a geo-environmental problem. Initial UCG process requires water for gasification of coal. Once the UCG process started cavity gradually increase. During burning process, cavity pressure is controlled for water influx and gas losses. Upon completion of burning, water present in aquifer begins to seep back into the burn cavity which

**Table 2.** Baseline and maximum reported inorganic contaminates concentrations in six sites (Ahern and Frazier, 1982).

Type of inorganic constituents	Hoe Creek I		Hoe Creek II		Hanna I		Hanna II		Fairfield		Tenn. Colony	
	Base	Max.	Base	Max.	Base	Max.	Base	Max.	Base	Max.	Base	Max.
<b>Cations(mg/L)</b>												
Ammonium	0.6	72	-	-	2.3	15	-	-	1.0	100	0.7	16.3
Boron	0.09	0.5	-	0.8	0.06	1.5	0.06	0.3	-	0.3	0.03	2.2
Calcium	36	220	-	-	15	32	-	6	20	8	8	94
Iron	0.01	37	-	-	0.04	8	0.03	0.1	-	200	0.9	92
Lead	0.001	0.041	-	-	0.03	0.03	-	-	-	-	ND	ND
Magnesium	10	60	-	-	9	15	-	-	5	15	2	22
Manganese	-	-	-	-	0.06	0.06	-	-	-	0.07	0.06	1.3
Zinc	-	-	-	-	0.2	0.9	-	-	-	ND	1.8	7
Mercury	ND	ND	ND	ND	0.001	0.0001	0.001	0.0001	ND	ND	ND	ND
<b>Anions (mg/L)</b>												
Cyanide	0.01	290	-	-	-	-	-	-	-	940	ND	0.008
Sulfate	150	1230	-	-	400	1600	-	-	4	1150	1	625
Thiocyanate	-	-	-	-	-	-	-	-	-	ND	ND	0.3

ND-Not Determined.

**Table 3.** Baseline and maximum reported inorganic contaminates concentrations in six sites (Ahern and Frazier, 1982).

Constituents	Hoe Creek I		Hoe Creek II		Hanna I		Hanna II		Fairfield		Tenn. Colony	
	Base	Max.	Base	Max.	Base	Max.	Base	Max.	Base	Max.	Base	Max.
TDS (mg/L)	700	3400	-	-	1700	3300	-	-	350	2300	290	1460
pH	7.5	6.3	-	-	-	-	-	-	-	7.6	8.3	5.8

contains ash and rubble. Permeability in the cavity is assumed to be several orders of magnitude greater than that in the coal seam and porosity in the cavity is assumed to approach unity (Contractor and Schreiber, 1987). During water filling stage, products of combustion contaminate ground water. After a certain time, the cavity fills up and becomes part of the confined aquifer

system. Storage coefficient of the cavity is now larger than that of the coal seam. A time is reached when flow occurs out of the cavity, taking with it the contaminants to be dispersed and sorbed in the aquifer. As started before and after gasification water in the coal seam (adjacent to the cavity) flows into it, picking up pollutants from the ash and char zone, and migrates from the

cavity to adjacent aquifers (Sury et al., 2004).

### Groundwater restoration

After completion of UCG process many organic and inorganic contaminants left in cavity, generated after UCG process. Phenol concentration in

groundwater is found in large amount because its solubility in water is high. Groundwater is function of time and distance from the reactor (Campbell et al., 1979). So, concentrations of contaminated groundwater restore as fresh water after a long time. Inorganic contaminants, including cations such as  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Mg}^{2+}$ ,  $\text{NH}_4^+$  etc. and anions such as  $\text{SO}_4^{2-}$ ,  $\text{HCO}_3^-$ ,  $\text{Cl}^-$  etc. also showed a large decrease in concentration over time (Nordin, 1992).

## MITIGATION OF GROUNDWATER CONTAMINATION

### Site selection

Appropriate site selection is the best approach for groundwater pollution control. Before starting UCG process ensure the site is well characterized and the coal seam has limited connectivity with water sources. Therefore, selecting sites with favorable hydrogeology minimizes movement of contaminants. Selection of regions where overburden is expected to deform plastically reduces the concern of shearing of strata. Shearing can result in vertical propagation fractures that allows fluid communication between the gasification zone and surrounding groundwater (Moorhouse et al., 2010).

### Appropriate sealing of wells and boreholes

Before starting UCG operation ensures that wells and boreholes used in the process are adequately sealed and maintain a 'cone of depression' in the groundwater around the reactor (Sury et al., 2004). Researchers have proposed several control technologies for containment, such as a hydraulic bypass around the contaminated zone, placing adsorbent clays within the cavity, placing a grout curtain around the contaminated zone and permeable reactor barrier. The permeable reactor barrier is filled with granulated activated carbon and peat for removal of hydrocarbons (Lutynski and Suponik, 2013). These contaminants are removed by physicochemical, chemical and biological processes.

### Controlling the reactor pressure

Migration of hazards elements from UCG cavity could be reduced by maintaining reactor pressure ( $P$ ) below the hydrostatic pressure ( $P_h$ ). Installation of operational monitoring systems is used to detect gas losses and ensure that reactor pressure is maintained below hydrostatic. In this case, water flow from the surrounding aquifer in to the UCG cavity, presents transport of contaminants into adjacent aquifers. It is also found that gas escape, which is driving force for contaminant dispersal, could be substantially reduced. Therefore, during UCG operation continuously measures the reactor pressure for mitigation measures (Friedmann et al., 2006).

### Pumping of contaminated water

Another concept for control would be pumping the contaminated water from the cavity and surrounding area, and treating or disposing of the water on the surface. This alternative would be effective for removal of highly mobile contaminants. These contaminants would consist of materials generated by ash leaching, such as soluble organic matter and ammonia (Cook and Oliver, 1983). Remaining material would be more insoluble and less mobile condensed organic matter around the periphery of the burn zone.

### Abandonment practices

At the time of shutdown of UCG process gasification zone cool slowly and gas is continue to extract until the gasification process stops completely. In this way contaminants can be evacuated out of the gasification zone before the site is abandoned. Monitoring of groundwater contaminates for a period of time after the site is abandoned. The actual duration of monitoring will depend on the specific site (Moorhouse et al., 2010).

## CONCLUSIONS

Groundwater pollution caused by UCG due to migration of water and gas dispersion to the surrounding permeable strata. The major pollutants identified in groundwater include organic and inorganic substances, TDS etc. Concentration of these pollutants decrease by increase of distance from the cavity, and after some time these decrease due to restoration of pollutant water. Migration of contaminated groundwater and restoration as well as some mitigation measures are specified for pollution free UCG operation. Major organic and inorganic substances, TDS and pH data indicate that baseline and maximum contaminated groundwater constituents vary depending on types of coal and operating parameters of UCG.

### Conflict of Interest

The authors have not declared any conflict of interest.

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## REFERENCES

Ahern JJ, Frazier JA (1982). Water quality changes at underground coal



- gasification sites- a literature review. Laramie Energy Technology Center, U.S. Department of Energy, under contract DE-AS20-79LCO1761. Available at, [http://uwyo.coalliance.org/fedora/repository/wyucgchanges-at-underground-coal-gasification-sites\\_718e4862c1.pdf](http://uwyo.coalliance.org/fedora/repository/wyucgchanges-at-underground-coal-gasification-sites_718e4862c1.pdf), 5 June 2014.
- Burton E, Friedmann J, Upadhye R (2004). Best practices in underground coal gasification. Lawrence Livermore National Laboratory. Available at, <https://www.purdue.edu/discoverypark/energy/assets/pdfs/cctr/BestPracticesinUCG-draft.Pdf>, 12 June 2014.
- Campbell JH, Wang FT, Mead SW, Busby JF (1979). Groundwater quality near and underground coal gasification experiment. *J. Hydrol.* 44:241-266.
- Contractor DN, Schreiber JD (1987). Field applications of multi-aquifer ground water models for flow and transport to underground coal gasification sites. Available at, <http://info.ngwa.org/gwol/pdf/870142817.pdf>, 10 June 2014.
- Cooke DS, Oliver RL (1983). Groundwater quality at the Hanna underground coal gasification experimental sites, Hanna, Wyoming: Database and Summary. U. S. Department of Energy/Associated Western Universities, Inc. under cooperative contract (DE-AC07-76ET10723). Available at, [http://www.fraw.org.uk/files/extreme/cooke\\_oliver\\_1984.pdf](http://www.fraw.org.uk/files/extreme/cooke_oliver_1984.pdf), 15 June 2014.
- Friedmann SJ, Burton E, Upadhye R (2006). LLNL capabilities in underground coal gasification, Work performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under contract W-7405-Eng-48.
- Green MB (1999). Underground coal gasification - A joint European field trial in Spain. ETSU Report No. COAL R169. DTI/Pub URN99/1093.
- Haider Z (2012). Site characterization, sustainability evaluation and life cycle emissions assessment of underground coal gasification, Ph.D thesis. Available at, [http://scholar.lib.vt.edu/theses/available/etd-09132012-155859/unrestricted/Hyder\\_Z\\_D\\_2012.pdf](http://scholar.lib.vt.edu/theses/available/etd-09132012-155859/unrestricted/Hyder_Z_D_2012.pdf), 12 June 2014.
- Humenick MJ, Lang M (1980). The effect of lignite ash composition on ground water leachate. In Proceedings 6<sup>th</sup> Symposium on Underground Coal Conversion, V38-V44.
- Lang MJ (1982). Groundwater leaching of lignite ash after underground coal gasification. Master of Science thesis, The University of Texas, Austin. Available at, [http://www-lib.uwyo.edu/showcase/files/original/ground-water-leaching-of-lignite-ash-after-underground-coal-gasification\\_5e52d66fb7.pdf](http://www-lib.uwyo.edu/showcase/files/original/ground-water-leaching-of-lignite-ash-after-underground-coal-gasification_5e52d66fb7.pdf), 10 June 2014.
- Lutynski M, Suponik T (2013). Hydrocarbons removal from underground coal gasification water by organic adsorbents. *Physicochem. Prob. Min. Proc.* 50(1):289-298.
- Moorhouse J, Huot M, McCulloch M (2010). Underground coal gasification: Environmental risks and benefits. Available at, <http://www.pembina.org/reports/laurusreport.pdf>, 8 November 2014.
- Nordin SJ (1992). Review of information and data relevant to Hoe Creek underground coal gasification site restoration. Western Research Institute, The University of Wyoming Research Corporation, Laramie, Wyoming. Available at, <http://deq.state.wy.us/>, 11 June 2014.
- Phillips NP, Muela CA (1977). In-situ coal gasification: status of technology and environmental impact. Interagency Energy-Environment Research and Development Program Report, EPA-600/7-77-045.
- Shu-qin L, Yuan-yuan W, Ke Z, Ning Y (2009). Enhanced-hydrogen gas production through underground gasification of lignite. *Min. Sci. Technol.* 19:389-394.
- Stephens DR, Hill R, Wand Borg IY (1985). Status of underground coal gasification. UCRL 92068. *Int. J. Miner. Process. Extract. Metallurg Rev.* 1(3-4):265-296.
- Stone R, Raber E, Winslow AM (1982). Effects of aquifer interconnection resulting from underground coal gasification. *Ground Water* 21(5):606-618.
- Stuermer DH, Ng DJ, Morris CJ (1982). Organic contaminants in groundwater near an underground coal gasification site in Northeastern Wyoming. *Environ. Sci. Technol.* 16(9):582-587.
- Sury M, White M, Kirton J, Carr P, Woodbridge R, Mostade M, Chappell R, Hartwell D, Hunt Douglas, Rendell N (2004). Review of environmental issues of underground coal gasification. WS Atkins Consultants Ltd., University of Liège Belgium, FWS Consultants Ltd., 126. Report No. COAL R272 DTI/Pub URN 04/1880, pp. 1-126.
- Torres VN, Atkins AS, Singh RN (2014). Assessment of an environmental sustainability index for the underground coal gasification process by using numerical analysis. In Proceedings of the 14<sup>th</sup> Coal Operators' Conference, University of Wollongong, Australasian Institute of Mining and Metallurgy, Mine Managers Association of Australia, pp. 309-323.
- Wang F (1979). The sportive property of coal. In Proceedings of the 5<sup>th</sup> Underground Coal Conversion Symposium, U.S. Dept. Energy, Rep. CONF. 790630, pp. 403-408.