

Underground Coal Gasification (UCG) November 2015



Contents

Summary	3
1.0 What is Underground Coal Gasification?	3
1.1 The UCG Process	3
1.2 Decommissioning	4
2.0 Uses for Syngas	5
3.0 Treatment of Syngas	5
4.0 History of UCG.....	6
5.0 Environmental Impacts	6
5.1 UG Contaminants	7
5.2 Groundwater Contamination	7
5.3 Air Pollution.....	8
5.4 Climate Impacts	9
5.5 Solid Wastes and Waste Water	9
5.6 Subsidence	10
6.0 The Australian Experience.....	10
6.1 Commercialisation Stalled	11
7.0 Litigation Against Linc Energy	11
7.1 Excavation Exclusion Zone.....	13
8.0 Conclusion	13
Annex 1.....	14
UCG chemicals and contaminants	14
Endnotes.....	17

Underground Coal Gasification (UCG)

October 2015

This report is intended to be a living document and will be updated as new important information is released.

Summary

Syngas – the Energy from Hell

In 1913, Vladimir Lenin described underground coal gasification (UCG) as the ‘Great Victory of Technology’ promising to liberate workers from the hazardous work in the mines. Today, the people from South-East Queensland, Australia call it ‘*Syngas - the Energy from Hell*’. Underground Coal Gasification (UCG) is an industrial process that produces both air and water contaminants in large amounts. The environment is not only at risk from these contaminants but also from the industrialisation of strategic agricultural land. The Australian experience has shown that the industry is unable to fully control its toxic emissions and that UCG carries significant risks to human health, agriculture and the environment.

1.0 What is Underground Coal Gasification?



Underground Coal Gasification (UCG) is an industrial process, which converts coal into product gas. UCG product gas is a mix of carbon dioxide (CO₂), hydrogen, carbon monoxide (CO), methane (CH₄), nitrogen, steam and gaseous hydrocarbons, produced by partially combusting underground coal in the presence of water with a controlled oxygen supply. The proportion of the gases varies with the type of coal as well as the efficiency and control of the gasification process.

1.1 The UCG Process

Unlike gasification in industrial reactors, which produce syngas, UCG is an *in-situ* gasification process remotely carried out underground usually in non-mined coal seams.ⁱ Gasification is typically conducted at a temperature between 900 and 1200 degrees C but may reach up to 1500 C, the resultant product gas is also commonly referred to as synthesis gas or Syngas.ⁱⁱ

At the start of the UCG operation, injection wells deliver ignition agents like propane or ammonium nitrate fuel oil, as well as air, steam and/or oxygen to initiate combustion. Once combustion is established in the coal seam, the injection wells

inject air, steam and/or carbon dioxide in an attempt to sustain and control the combustion rate.

The combustion converts carbon in the coal to CO₂ and heat. This heat drives secondary reactions between CO₂ and water to produce CO, hydrogen gas (H₂) and CH₄. The gases are then extracted through a production well, leaving the tar, solid char and bottom ashes in the chamber cavity.

Between the combustion zone and the production wells, the gas flows through the coal seam. To facilitate the flow, a 'link' from the combustion zone to the production well(s) is created by using hydraulic fracturing, directional drilling, reverse combustionⁱⁱⁱ or explosive fracturing.^{iv v}

There are two different UCG methods; one uses vertical wells and reverse combustion to open up internal pathways in the coal. The other method creates dedicated in-seam boreholes, using drilling technology adapted from oil and gas production. It utilises a moveable injection point known as CRIP (controlled retraction injection point).

UCG wells are generally less than 200 metres deep although they have been tested at depths of approximately 800 metres (e.g., Thunder Basin, Wyoming). The wells need to be constructed to withstand exposure to extreme thermal and mechanical stresses associated with high pressures, extremely high temperatures, and potential subsidence of the cavity roof. Coal seam thickness is crucial as a decrease in the seam thickness can reduce the heating value of the produced gas. Gas heating value can decrease significantly if the seam thickness falls below 2 metres.^{vi}

The main mechanism for preventing contaminant migration during UCG operations is the maintenance of gas pressures within the gasifier, which must remain lower than the equivalent hydrostatic pressure of the groundwater within the coal seam and the surrounding strata. If a net pressure gradient is maintained towards the gasifier chamber, the gas and the associated contaminants are less likely to move away from the site of the combustion, unless faults and fissures are present.

UCG operations have a degree of imprecision and cannot be well controlled. There are many variables like the rate of water influx, the distribution of reactants in the gasification zone and the growth rate of the chamber cavity. These can only be estimated from temperature measurements, and analyzing product gas quality and quantity.^{vii}

1.2 Decommissioning

An essential component of UCG is the decommissioning and remediation of the chamber cavity. The final shutdown sequence for a UCG panel is considered complex with a medium to long-term timeframe.^{viii} The aim is to extinguish the reaction by limiting the supply of oxygen and bring the materials surrounding the

cavity into thermal equilibrium with the surrounding coal seam and over- and underlying strata. ^{ix} Sometimes, this may not be easily achieved, e.g., Jharia in India has a coal fire that has burned underground for approximately 100 years due to inability to ensure that the supply of oxygen has been completely cut off.

As the cavity cools, there is the high probability that toxic chemicals will be formed. *'There is an inherently high probability of the formation of potentially contaminating chemicals e.g., benzene, toluene, xylene (BTEX), phenols, various polycyclic aromatic hydrocarbons (PAHs) and other hydrocarbons. This is a result of the ongoing coal pyrolysis at temperatures between 250°C and 700°C, which favour their formation and so cooling of the reactor cavity will inevitably produce these unwanted chemicals.'* ^x

Decommissioning also requires the cavity to be cleaned. Decreased pressure is used to draw the groundwater towards the cavity bringing any residual chemicals from the active zone into the cavity. The residual heat in the cavity is used to vaporise the water and contaminants, which are then brought to the surface for treatment. Upon completion of burning, water present in aquifer begins to seep back into the cavity, which still contains ash, tar and rubble. The cavity will eventually be filled with a combination of the rubble from the gasified coal, the collapsed overburden and disturbed underburden, as well as groundwater. ^{xi} However, the Queensland Independent Scientific Panel (ISP) noted that if the post-gasification cavity is at least partially rubble-filled from the overburden it implies that the integrity of the seal is potentially compromised.

2.0 Uses for Syngas



The UCG process produces gases that can be burned to generate heat or electricity, or can be liquefied and refined to produce fuel. The Gas to Liquids (GTL) process is a chemical conversion process whereby UCG syngas is transformed into synthetic crude ('syncrude'), which can then be refined using traditional methods to produce cleaner diesel and jet fuels. Syngas can be used for the manufacture of chemicals, such as ammonia and fertilizers, explosives and other products and the production of hydrogen. It has been argued that long-distance transportation of the gas decreases the economic effectiveness; thus, it is argued the best approach is to use it for power generation or for conversion to other products near the UCG site. ^{xii}

3.0 Treatment of Syngas



Depending on its proposed use, the gas will require treatment. For example, treatment to remove of sulfur containing compounds like hydrogen sulfide (H₂S) is usually considered essential to the final

application of the gas and is done using a range of industrial chemical products.^{xiii} Other technologies are used for the removal of particulates and tar, ranging from physical treatments such as cyclone separators, barrier filters, electrostatic precipitators and wet gas cleaning or wet scrubbers to thermal processes like thermal cracking, dry gas cleaning and plasma methods. Wet gas cleaning of syngas uses liquid scrubbing agents in a scrubber system.^{xiv}

4.0 History of UCG



The former Soviet Union initiated a research and development program in the 1930s, which led to several industrial-scale UCG plants. By the 1960s, five UCG gas plants were operating but the only remaining commercial UCG site is now in Angren, Uzbekistan.^{xv} In the USA, UCG tests were conducted in Alabama in the 1940-1950s and many more were undertaken between 1972 and 1989 at various localities including Wyoming, Texas, Washington and Virginia. Several of these US UCG operations e.g., at Hoe Creek and Rock Springs, Wyoming and Rio Blanco, Colorado resulted in serious groundwater contamination.^{xvi}

In the 1980s, trials were conducted in France and Belgium, but these were not successful, despite their use of the new techniques of hydraulic fracturing and reverse combustion. In the 1990s, a UCG project was conducted in Spain but was concluded when a malfunction caused a build up of methane, resulting in an explosion.^{xvii} In the U.K., a prefeasibility study was completed in early 2000 and work began on selecting a U.K. trial site.

While little detail is known of UCG activities in China, it is reported that China has conducted 16 UCG pilot projects since 1991. There are also media reports that in 2014, SinoCoking Coal and Coke Chemical Industries signed an agreement with the Institute of Process Engineering of the Chinese Academy of Sciences and the North China Institute of Science and Technology to refine and implement a technology that will be used to convert the 21 million tons of coal at four SinoCoking underground mines into syngas.^{xviii}

5.0 Environmental Impacts



UCG has been linked to a number of environmental impacts including contamination of ground water, air pollution, subsidence of the overlying terrain, and climate change exacerbation. Proponents argue, that compared to traditional coal mining and processing, UCG eliminates surface damage and solid waste discharge, and reduces sulfur dioxide (SO₂) and nitrogen oxide (NO_x) emissions. However, the gaseous, liquid and solid waste streams, which accompany UCG are recognised as a source of known mutagenic and carcinogenic pollutants with the potential to contaminate groundwater.^{xix}

5.1 UG Contaminants

The combustion of coal produces a range of combustion by-products and residuals, including ash and hydrocarbons that remain in the chamber formation. These can include highly toxic substances like mercury, phenol, benzene as well as dioxins and polycyclic aromatic hydrocarbons (PAHs). Combustion ash also typically contains metals, such as arsenic, cadmium, chromium, as well as cobalt, lead and selenium. The solubility of heavy metals in water is increased with combustion as they are no longer tightly bound together.

Naturally Occurring Radioactive Materials or NORMs, like uranium, thorium and their progeny Radium 228 and Radium 226 are found in coal seams.^{xx} The World Nuclear Association note that the amounts of radionuclides involved are noteworthy. Coal from the USA, Australia, India and the United Kingdom contain up to 4 ppm uranium, while those in Germany can range up to 13 ppm, and those from Brazil and China up to 20 ppm uranium. Thorium concentrations are often three times those of uranium. During combustion the radionuclides are retained and concentrated in the ash. The concentration of uranium and thorium in the ash can be up to ten times greater than for the burnt coal, while other radionuclides such as Lead 210 (²¹⁰Pb) and Potassium 40 (⁴⁰K) can concentrate to an even greater degree in the flyash.^{xxi} Little is known about the release of radioactive substances from UCG activities.

5.2 Groundwater Contamination

The natural fractures and joints of the coal seams and surrounding rock provide pathways for water and gas migration both into and from the chamber cavity. Once the cavity is full, water can flow out taking with it contaminants to be dispersed into surrounding soil and groundwater.^{xxii} These conditions, combined with the water solubility of the contaminants, provide opportunities for relatively high mobility of contaminants.

Despite industry claims, it is unclear whether isolating a UCG operation from surrounding groundwater is even possible as heating and subsidence from UCG can lead to fractures that change groundwater flow.^{xxiii} Monitoring UCG for compounds like benzene, ethylbenzene, toluene, and xylenes (BETX), polycyclic aromatic hydrocarbons (PAHs) and phenolic compounds along with inorganic contaminants is considered essential.^{xxiv}

A large number of hazardous water-borne contaminants have been identified during different UCG operations conducted so far, and in some locations, there was long-term groundwater contamination. The organic pollutants detected after UCG process include phenols, benzene with its derivatives, polycyclic aromatic hydrocarbons (PAHs), heterocycles, ammonia, mercury, zinc, sulphates, cyanides and other heavy metals.^{xxv} Phenol concentration in groundwater was high due to its high solubility in water.^{xxvi}

UCG operations in the USA at Hoe Creek and Rock Springs, Wyoming and Rio Blanco, Colorado have resulted in groundwater contamination. The primary

contaminants were phenols and benzene with some, including ammonia, nitrate, and benzene, found to exceed health-based standards in groundwater at one or more UCG sites.^{xxvii}

After UCG pilot-scale test burns at Hoe Creek, groundwater samples collected indicated that the collapse of the roof of the chamber cavity caused by gasification had interconnected three aquifers. Samples from more than twelve wells in the vicinity of the UCG site showed a greatly increased concentration of organic and inorganic compounds released from the residual ash. Combustion products including phenols and benzene were introduced into the groundwater system. The U.S. Department of Energy concluded that groundwater contamination at the site posed potential future risk to humans and livestock ingesting water from nearby wells, as well as risk to wetlands habitat situated down gradient of the site.^{xxviii}

5.3 Air Pollution

The UCG process releases toxic gases throughout the construction phase, operational phase and decommissioning. Potential sources of emissions associated with the UCG facility have been identified as:

- emissions associated with construction and transport;
- gas generated through the coal gasification processes;
- venting during start-up to dry the gasifier for normal operation;
- flaring of the UCG pilot plant and safety valves during regular or upset conditions; and
- gas engine exhaust emissions.

A consultant's assessment^{xxix} for the proposed UCG facility in South Africa concluded that: *"Based on the available data; construction and operation of the proposed UCG facility, will impact negatively on local ambient air quality."* They noted that venting during 'upset' conditions would result in carbon monoxide (CO) emissions and that flaring during 'upset' conditions and ongoing gas exhaust emissions would result in CO, NO₂ and SO₂ emissions that would affect ambient air quality.

During start-up, raw gas is flared and the associated emissions include particulates (soot), unburned hydrocarbons, CO, NO_x, PAHs, products of incomplete combustion and in some cases, H₂S or SO₂. The quantities of hydrocarbon emissions generated relate to the degree of combustion while the flare rate is based on the capacity and production rate of the facility.

In assessing the impacts of UCG on air quality, it is essential to take into account the suite of fugitive emissions, which will inevitably occur. In Australia, the Queensland government has alleged that gaseous pollution from the Linc Energy UCG plant has affected a wide area of land.

5.4 Climate Impacts

The World Energy Council estimates that UCG could increase the economic recovery of 600 billion tonnes of coal reserves, allowing companies to access coal that has previously been considered 'unminable'.

"Per unit of energy, burning coal releases more of the CO₂ that contributes to global warming than any other fuel and UCG is no exception."^{xxx}

As energy from the coal in UCG is also expended heating rock, more coal must be burned and thus more CO₂ generated in order to produce the same amount of energy. Add to this transportation and mining emissions and it is difficult to see how UCG can be thought of as climate friendly.

5.5 Solid Wastes and Waste Water

The UCG process produces large volumes of solid wastes and contaminated waste water including liquid effluents generated from gas scrubbing. In addition to gases rising to the surface in the production well, a significant amount of wastewater and solids are also present. The effluent consists of produced formation water, with particulates and dissolved gases, hydrocarbons and numerous salts. About 3-5% of UCG wastewater are solids, becoming sludge once settled out in the wastewater treatment plant.^{xxxi} These waste streams must be separated and managed post-extraction.

The findings of a 2015 study^{xxxii} that sought to identify the main organic and inorganic chemical and odoriferous properties of UCG wastewater and sludge from a site in Australia, confirmed that:

- UCG wastewater has a highly objectionable odour and is contaminated with significantly high concentrations of benzene, alkanic hydrocarbons and phenols; and
- UCG sludge has an equally objectionable odour and contains even higher concentrations of BTEX, total petroleum hydrocarbon (TPH) and phenols.

Phenols were detected at extremely high concentrations between 5,550 ppm and 21,000 ppm in the UCG waste. The study noted that phenols, which are mutagenic and possibly carcinogenic, can also cause headaches, nose, throat and lung irritation as well as damage the liver, kidneys and central nervous system.^{xxxiii}

In Linc Energy's initial advice to government on their joint UCG and coals to liquid project noted that *'operation of the pilot burn resulted in increased levels of phenol benzene and PAH in the condensate.'*^{xxxiv}

Typically, management of these wastes have included some treatment for the liquid effluents and then subsequent reuse, e.g., for irrigation. Gaseous effluents would be vented while post treatment and solid wastes from water treatment would be sent to

landfill. Ash or slag would remain at the point of gasification in the underground cavities.^{xxxv}

5.6 Subsidence

Subsidence may be inevitable with UCG because the supporting coal layer is burnt, leaving only residual ash and a void. Many UCG projects propose to gasify coal seams that are deep enough to be inaccessible to conventional mining, and therefore the subsidence at the surface may be minimal. However, while deep subsidence may be invisible on the surface, it can affect groundwater flow.

6.0 The Australian Experience



There have been three UCG pilot or trial projects in Australia. In South East Queensland, the Carbon Energy trial site operated west of Dalby, while the Linc Energy site was near the rural towns of Chinchilla and Hopeland. The Cougar Energy trial was conducted in Kingaroy, North Queensland

Cougar Energy started up in March 2010 and was ordered to close due to benzene and toluene contamination of nearby bores in July 2010.^{xxxvi} Charges were laid relating to the rupture of a production well that resulted in the release of the UCG contaminants, benzene and toluene to the groundwater. The company pleaded guilty to three breaches of the *Environmental Protection Act 1994* and was later fined \$75,000 for leaking benzene into groundwater at its UCG project.^{xxxvii}

Carbon Energy commenced in 2008 and started its decommissioning phase 2012. Charges were laid against the company for allegedly breaching conditions of its environmental authority and failing to notify the department in 2009. The charges relate to a spill of process water into nearby Bloodwood Creek which was not reported to the department as required.

The company was also charged with disposing of process water by irrigating it to land without approval. Carbon Energy pleaded guilty to the three charges and was fined \$60,000.^{xxxviii} The company's executive officer also pleaded guilty to failing to ensure that Carbon Energy complied with the *Environmental Protection Act 1994* and was fined \$2000.^{xxxix}

After conducting a site inspection in June 2010, the Department of Environment and Resource Management issued an Environmental Protection Order preventing the recommencement of UCG activities at the trial plant. The department has since lifted the order and issued the company new environmental authorities in February 2011. In 2012, the ISP found that Carbon energy site design envisages multiple combustion sites, yet had still not provided a full site monitoring plan.

Linc Energy's demonstration facility operated from 1999 with decommissioning starting in 2013. Linc trialled 5 different gasifier operations and a gas-to-liquids (GTL)

plant on site. In one 30-month test period, Linc Energy gasified approximately 35,000 tonnes of coal at a depth of 120 metres below surface with the majority of the gas being flared to the atmosphere. In 2007, Linc commenced construction of its GTL pilot plant, with the first synthetic crude produced in October 2008.

In 2013, the ISP^{xi} established by the Queensland State Government questioned Linc Energy's selection of the Chinchilla site because of the unsuitability of the local geology.

6.1 Commercialisation Stalled

In July 2014, the Queensland government, on the recommendation of the ISP,^{xii} refused approval for commercialisation until the industry could prove that UCG projects can be safely decommissioned i.e., they could put out the fire, remediate the chamber and prevent groundwater contamination. The ISP wanted evidence that the combustion process of the underground coal could be safely drawn to a close and that there was no issues associated with it. The ISP stated that neither Carbon Energy nor Linc Energy provided sufficient information on the operation and decommissioning of their previous cavities or currently operating panels to reach the conclusion that they were safe.

The ISP made the following recommendation;

'Specific Recommendation #4 No further panels should be ignited until the long term environmental safety provided by effective decommissioning is unambiguously demonstrated. Evidence of the effectiveness of decommissioning must be comprehensive.'

7.0 Litigation Against Linc Energy



In April 2014, the Queensland Government's environment department filed four charges against Linc Energy over the alleged contamination of the environment by its UCG facility. In 2015, the Government filed a fifth charge of willfully and unlawfully causing serious environmental harm. They alleged the harm was both on-site and offsite.

An investigation^{xiii} commissioned by the Queensland government Environment Department concluded that Linc Energy's UCG plant had caused irreversible damage to the atmosphere, vegetation, water and soil. It is reported^{xiiii} that concentrations of hydrogen in the soil were at explosive levels and abnormal amounts of methane were found over a wide area. The region affected is a fertile part of the Western Darling Downs and is used to grow wheat, barley and cotton and for cattle grazing, with some organic producers.

The investigation by consultants Gilbert & Sutherland and the University of

Queensland tested air, water and soil samples and reported that carcinogenic volatile organic compounds and other gases were found over a wide area around the Linc facility.

"We have found gases in quantities above the explosive limit. In our reconnaissance of boreholes, explosive levels have been found that indicate very much higher concentrations in the soil atmosphere."

Workers report instances of gas bubbling from the ground forming puddles and a black tar like substance associated with the bubbles. The operators also reported repeatedly detecting gas in the atmosphere via their personal gas detectors.^{xiv}

The national broadcaster, ABC, reported the findings of the still as yet confidential investigation, which concluded:

"The degree of contamination is widespread, of high impact and, in part, irreversible. it pervades an area of high conservation value to the north of Linc's site ... and while the full extent of the spread and concentration of the indicator gases has, as yet, not been confirmed, it is widespread (>20 to 310km²)."

The consultants' report note the contamination was caused by the release of syngas, its component gases and by-products, as well as via contaminated groundwater, tars and other petroleum products and odours, in the form of phenols and other products. This had most likely occurred when the chamber overburden (the 'safety blanket') was breached, probably as early as 2007. They noted that the combination of contaminants in the form of gas-liquid mixtures would likely undergo further environmental transport causing future contamination. Having dispersed the contaminants to the overburden and the soil profile, these were at risk of release during normal land use and agricultural activities. This would potentially expose farmers and landholders to contaminants over time and potentially, impact on soil, ecological health and land use.

Importantly, it was confirmed that the contaminants identified and measured both on and off the site were products or by-products of UCG activities and that they exhibited the 'same gas fingerprint'. The investigation concluded that: *"No other activity or source of hydrogen or other contaminants in the vicinity that could be credibly linked to or account for the results were encountered."*

Other documents, released to the ABC by the magistrate in charge of the criminal case, show departmental investigators were hospitalised with suspected gas poisoning during soil testing at the site in March 2015. It was reported that high levels of benzene were detected at the site afterwards.

The documents filed in the Supreme Court in Brisbane^{xiv} also alleged a series of unreported incidents at the plant including a fire that caused the evacuation of the site in 2007 and persistent leaks of toxic gas into the air and groundwater between 2008 and 2011. The Queensland government has informed residents that further details from testing and sampling will be available later in 2015.

The court documents also contain further claims that the health of workers at the plant had been affected. Staff had complained of bleeding noses, dizziness, nausea and vomiting, headaches, blurred vision and respiratory ailments after being exposed to odours from the waste storage dams. The documents allege that staff had reported the incidents and related gas releases to the company but none was ever reported to the appropriate government authorities. Staff had been required to sign confidentiality agreements, which prevent disclosure of matters concerning the Linc facility.

7.1 Excavation Exclusion Zone

The Queensland Government has imposed an "excavation exclusion zone" on 314 square kilometres around the Linc facility where landholders are banned from digging deeper than two metres. They have installed 52 long-term soil monitoring bores.

Linc Energy announced it would cease operations at the site in August 2013^{xlvi} after 14 years of operational trials, however, flaring continues at the Linc site due to the presence of methane,. The Queensland government has requested \$22 million in additional financial guarantees to cover the cost of cleaning up the water and sediment in several storage dams at the facility, which the department claims are "likely" to be contaminated with dioxins and other pollutants. Linc is refusing to provide the guarantee and has taken the matter to the Land Court.

Despite the charges and alleged environmental damage, in September 2015, Linc Energy's website still claims that they "offer a cleaner, more affordable and safer energy alternative" through their "proven, world-leading underground coal gasification (UCG) technology.

8.0 Conclusion



UCG has failed to show it is either a safe or an effective form of energy production. UCG trials have repeatedly resulted in contamination of air and water and the Australian experience has shown that the industry is unable to control its toxic emissions. As with all fossil fuels, UCG further exacerbates climate change. Australia's experience with UCG demonstrates that this technology carries significant risks to human health, agriculture and the wider environment. Not only has it cost workers their health, local communities and farmers their future but has provided a significant impost on the public purse with the current Queensland government investigation costing \$6.5 million. The potential hazards to human health, agriculture and the wider environment are far too serious to take the risks associated with UCG development.

Annex 1

UCG chemicals and contaminants

BTEX (benzene, toluene, ethylbenzene, xylene)

BTEX chemicals are naturally occurring volatile organic compounds found in the coal deposits and associated groundwater.^{xlvii} Drilling and other UCG processes release BTEX from the coal seam. Their short-term health effects include skin, eye and nose irritation, dizziness, headache, loss of coordination and impacts to respiratory system while chronic exposure can result in damage to kidneys, liver and blood system.



Toxic

Benzene can cause leukemia, non-Hodgkin's lymphoma and also affects the immune system. It can cause chromosomal aberrations and mutations in human and animal cells.^{xlviii} It has also been linked to birth defects^{xlix} and sperm abnormalities^l. The World Health Organisation identified exposure to benzene as a major public health concern. They note that benzene is a well-established cause of cancer in humans with the International Agency for Research on Cancer classifying benzene as carcinogenic to humans (Group 1).

Phenols

The New Jersey Department of Health considers phenols are mutagenic^{li} and while classified as a Group D, not classifiable as to human carcinogenicity, based on a lack of data, they note as a mutagen it may have a cancer risk. Dermal studies have reported that phenol applied to the skin may be a tumor promotor and/or a weak skin carcinogen in mice. Phenol can cause headaches, nose, throat and lung irritation as well as damage to the liver, kidneys and central nervous system. It is highly irritating to the skin, eyes and mucous membranes in humans after acute inhalation or dermal exposures. Anorexia, progressive weight loss, diarrhea and blood and liver effects have all been reported in chronically exposed humans.^{lii} Animal studies have demonstrated growth retardation and abnormal development in the offspring of animals exposed to phenol by the oral route. Phenols are extremely soluble in water and in the presence of chlorine in water can form chlorophenol. The presence of phenol in water resources can affect water quality and aquatic organisms.^{liii}

Polycyclic Aromatic Hydrocarbons (PAHs)

PAHs are a group of very toxic volatile compounds. They are created when products like coal, oil, gas, and garbage are burned but the burning process is not complete. PAHs are persistent and can stay in the environment for long periods of time. Individual PAHs vary in behavior. Some can turn into a vapor in the air very easily. Most do not break down easily in the water.^{liv} PAHs have caused tumors in laboratory animals exposed to PAHs through food, contaminated air, or skin contact. Some PAH metabolites interact with DNA and are genotoxic, causing malignancies and heritable genetic damage in humans. Heavy occupational exposure to mixtures of PAHs entails a substantial risk of lung, skin, or bladder cancer.^{lv} Research^{lvi} indicates that people living or working near active natural gas wells may be exposed to pollutants at higher levels than the US EPA considers safe for lifetime exposure.

Volatile Organic Compounds

Volatile organic compounds (VOCs) are organic compounds that easily become vapors or gases. They are released from burning fuel like coal or natural gas, emitted from oil and gas fields and diesel exhaust and are released during drilling, flaring, hydraulic fracturing or from wastewater holding ponds as well as from equipment and machinery. Many VOCs are hazardous air pollutants and when combined with nitrogen oxides, react to form ground-level ozone, or smog. VOC exposure may result in eye, nose, and throat irritation, headaches, visual disorders, memory impairment, loss of coordination, nausea, damage to liver, kidney, and central nervous system.^{lvii} Some VOCs cause cancer in animals (e.g. methylene chloride), in humans (e.g. formaldehyde) or are suspected human carcinogens (e.g. chloroform, bromodichloromethane). Some VOCs like formaldehyde and styrene are endocrine disrupting chemicals (EDCs).^{lviii}

Nitrogen Oxides

Two of the most common nitrogen oxides are nitric oxide (NO) and nitrogen dioxide (NO₂). Nitrous oxide is a greenhouse gas that contributes to climate change. Nitrogen oxides are emitted from machinery, compressors and flaring. Nitrogen oxides can react with VOCs to form ground-level ozone, which is linked to asthma attacks and other serious health effects. Nitrogen dioxide can cause respiratory problems, heart conditions and lung damage. It can interfere with the blood's ability to carry oxygen through the body, causing headache, fatigue, dizziness, and a blue color to the skin and lips. Long-term exposure to nitrogen oxides in smog can trigger serious respiratory problems, including damage to lung tissue and reduction in lung function. Exposure to low levels of nitrogen oxides in smog can irritate the eyes, nose, throat, and lungs. It can cause coughing, shortness of breath, fatigue, and nausea. Industrial exposure to nitrogen dioxide may cause genetic mutations, damage a developing fetus, and decrease fertility in women.^{lix}

Carbon monoxide (CO)

Carbon monoxide is a colorless, odorless, and tasteless gas, which is highly poisonous. It is produced by the incomplete burning of natural gas, liquefied petroleum gas, fuel, oil, kerosene, coal, charcoal and/or wood. Appliances that use these fuels may also produce CO and is also released during flaring. Exposure to low levels of carbon monoxide can cause fatigue, chest pain, shortness of breath, memory loss, skin lesions, sweating, and flu-like symptoms. Long term exposure to low levels can cause heart disease and damage to the nervous system. Exposure to high levels may result in impaired vision and coordination, unconsciousness, headaches, dizziness, confusion, vomiting, muscle weakness, and nausea while exposure to very high concentrations of CO can cause convulsions, coma, and death. CO may cause miscarriage or increase the risk of damage to a developing fetus and it may also result in babies with low birth weights and nervous system damage. Young children; pregnant women; elderly people; people with anemia, lung disease, or heart disease; people at high altitudes; or people who smoke cigarettes are more susceptible to the effects of CO.^{lx}

Sulfur dioxide (SO₂)

Sulfur dioxide is a colorless gas with a pungent odor. Most SO₂ in the air comes from the burning of coal and oil at electric power plants. SO₂ reacts with other chemicals like nitrogen oxides to form acid rain, which can damage lungs and cause respiratory illness, heart conditions and premature death. Breathing sulfur dioxide can irritate the nose, throat, and lungs, and cause coughing and shortness of breath. Long-term exposure to persistent levels of sulfur dioxide can cause chronic bronchitis, emphysema, and respiratory illness. It can also aggravate existing heart disease. Prolonged industrial exposure to sulfur dioxide may decrease fertility in men and women. Adults and children with asthma are sensitive to sulfur dioxide exposure.^{lxi}

Hydrogen sulfide (H₂S)

Hydrogen sulfide occurs naturally in some gas and coal formations and can be released when gas is vented or flared, or via fugitive emissions. It is a toxic gas, which is lethal if inhaled at high concentrations above 500 ppm. It irritates the lungs and respiratory tract and has a narcotic effect on the central nervous system. The reaction of H₂S with fluids in the nose and lungs forms sulphuric acid.^{lxii} H₂S is both an irritant and a chemical asphyxiant with effects on both oxygen utilization and the central nervous system. Its health effects can vary depending on the level and duration of exposure. Low concentrations irritate the eyes, nose, throat and respiratory system (e.g., burning/ tearing of eyes, cough, shortness of breath) while asthmatics may experience breathing difficulties. The effects can be delayed for several hours or sometimes several days when working in low-level concentrations. Repeated or prolonged exposures may cause eye inflammation, headache, fatigue, irritability, insomnia, digestive disturbances and weight loss. Repeated exposure can result in health effects occurring at levels that were previously tolerated without any effect. Moderate concentrations can cause more severe eye and respiratory irritation (including coughing, difficulty breathing, accumulation of fluid in the lungs), headache, dizziness, nausea, vomiting, staggering and excitability.^{lxiii}

Mercury

Mercury is a naturally occurring element that exists in various forms: elemental (or metallic) and inorganic and organic (e.g., methylmercury). These forms of mercury differ in their degree of toxicity and in their effects on the nervous, digestive and immune systems, and on lungs, kidneys, skin and eyes. Exposure to even small amounts of mercury may cause serious health problems and is a threat to the development of the child in utero and early in life. Mercury occurs naturally in the earth's crust and is released into the environment from volcanic activity, weathering of rocks and as a result of human activity particularly coal-fired power stations and residential coal burning for heating and cooking. Once in the environment, mercury can be transformed by bacteria into methylmercury, which then bioaccumulates in fish and shellfish. Mercury is considered by WHO as one of the top ten chemicals or groups of chemicals of major public health concern.^{lxiv}

Dioxins

Dioxins are a group of chemically-related compounds that are persistent environmental pollutants. The most toxic of the dioxin family is 2,3,7,8-tetrachlorodibenzo para dioxin (TCDD). Dioxins are found throughout the world in the environment and in living organisms including humans where they are

absorbed by fat tissue. In the environment, dioxins tend to accumulate in the food chain, mainly in the fatty tissue of animals. The higher an animal is in the food chain, the higher the concentration of dioxins. Dioxins are highly toxic and can cause reproductive and developmental problems, damage the immune system, interfere with hormones and also cause cancer. The developing fetus is most sensitive to dioxin exposure. Short-term exposure of humans to high levels of dioxins may result in skin lesions such as chloracne and patchy darkening of the skin, as well as altered liver function. Long-term exposure is linked to impairment of the immune system, the developing nervous system, the endocrine system and reproductive functions. Chronic exposure of animals to dioxins has resulted in several types of cancer. TCDD was evaluated by the WHO's International Agency for Research on Cancer (IARC) in 1997 and 2012. Based on animal data and on human epidemiology data, TCDD was classified by IARC as a "known human carcinogen"^{lxv}

Endnotes

ⁱ There is some evidence China is using the process in partially mined coal mines.

ⁱⁱ Independent Scientific Panel (ISP) Report On Underground Coal Gasification Pilot Trials June 2013 Queensland Independent Scientific Panel for Underground Coal Gasification (ISP) Professor Chris Moran, Director, Sustainable Minerals Institute, The University of Queensland. Professor Joe da Costa, School of Chemical Engineering, The University of Queensland. Em. Professor Chris Cuff, C&R Consulting, Townsville Queensland.

ⁱⁱⁱ Reverse combustion is achieved via ignition near the production well and counter-current flame propagation toward the injection well.

^{iv} Evgeny Shafirovich & Arvind Varma, Underground Coal Gasification: A Brief Review of Current Status *Ind. Eng. Chem. Res.* 2009, 48, 7865–7875

^v USEPA, The Class V Underground Injection Control Study Volume 13 In-Situ Fossil Fuel Recovery Wells http://water.epa.gov/type/groundwater/uic/class5/upload/2007_12_12_uic_class5_study_uic-class5_classvstudy_volume13-in-situfossilfuelrecovery.pdf

^{vi} Shafirovich et al 2009

^{vii} USEPA 2007

^{viii} ISP 2013

^{ix} *ibid*

^x *ibid*

^{xi} *ibid*

^{xii} Shafirovich et al 2009

^{xiii} For example, see http://www.dow.com/gastreating/solution/pa_scor.htm

^{xiv} L.C. Laurence and D. Ashenafi, Syngas Treatment Unit for Small Scale Gasification - Application to IC Engine Gas Quality Requirement *Journal of Applied Fluid Mechanics*, Vol. 5, No. 1, pp. 95-103, 2012.

^{xv} Shafirovich et al 2009

^{xvi} USEPA 2007

^{xvii} Shafirovich et al 2009

^{xviii} <http://www.coalage.com/news/latest/3871-chinese-launch-new-underground-coal-gasification-project.html#.VgyoVUtUPKM>

^{xix} Fergusson, L., A Study of Underground Coal Gasification (UCG) Wastewater and Sludge *Int. J. Environ. Res.*, 9(3):777-784, Summer 2015 Page 777-784

^{xx} Fact Sheet FS-163-97 October, 1997 Radioactive Elements in Coal and Fly Ash: Abundance, Forms, and Environmental Significance, USGS <http://pubs.usgs.gov/fs/1997/fs163-97/FS-163-97.html>

^{xxi} <http://www.world-nuclear.org/info/Safety-and-Security/Radiation-and-Health/Naturally-Occurring-Radioactive-Materials-NORM/>

- xxii Verma, R.P. et al, (2014) Review, Contamination of groundwater due to underground coal gasification, *Water Resources and Environmental Engineering*. Vol.6(12), pp. 303-311
- xxiii USEPA, The Class V Underground Injection Control Study Volume 13 In-Situ Fossil Fuel Recovery Wells http://water.epa.gov/type/groundwater/uic/class5/upload/2007_12_12_uic_class5_study_uic-class5_classvstudy_volume13-in-situ-fossil-fuel-recovery.pdf
- xxiv Shafirovich et al (2009)
- xxv Verma et al, (2014)
- xxvi Verma et al, (2014)
- xxvii USEPA 2007
- xxviii *ibid*
- xxix African Carbon Energy (Pty) Limited Air Quality Specialist Assessment for Underground Coal Gasification and Gas-Fired Power Generation Project REPORT January 2014 Report Number: 13615077-12437-6, Etienne Roux, Golder Associates Africa (Pty) Ltd
- xxx <http://groundtruthtrekking.org/Issues/AlaskaCoal/UndergroundCoalGasification.html#ixzz3lmC5k0uR>
- xxxi Fergusson, L., A Study of Underground Coal Gasification (UCG) Wastewater and Sludge *Int. J. Environ. Res.*, 9(3):777-784, Summer 2015 Page 777-784
- xxxii Fergusson 2015
- xxxiii *ibid*
- xxxiv <http://www.statedevelopment.qld.gov.au/resources/project/linc-energy/linc-energy-ias.pdf>
- xxxv Linc Energy UCG/CTL and Power Generation Project Chinchilla Initial Advice Statement, December 2006 <http://www.statedevelopment.qld.gov.au/resources/project/linc-energy/linc-energy-ias.pdf>
- xxxvi <http://www.miningaustralia.com.au/news/cougar-fined-over-leak-of-carcinogenic-chemical-at>
- xxxvii <http://statements.qld.gov.au/Statement/2013/9/24/cougar-energy-fined-75000-for-breaching-environmental-protection-act>
- xxxviii <http://statements.qld.gov.au/Statement/2012/12/6/carbon-energy-fined-for-releasing-contaminated-water>
- xxxix *ibid*
- xl ISP 2013
- xli *ibid*
- xliv Report on landform damage and alleged environmental harm from the Linc Energy Pilot trial, Chinchilla, Queensland June 2015: Gilbert & Sutherland. See <http://www.abc.net.au/news/2015-08-10/linc-energy-key-findings/6681938> Note this report remains confidential while the case against Linc Energy is prepared.
- xlvi <http://www.abc.net.au/news/2015-08-10/linc-energy-secret-report-reveals-toxic-chemical-risk/6681740>
- xlvii <http://www.abc.net.au/news/2015-03-17/linc-energy-accuse-failing-report-series-of-dangerous-leaks/6323850>
- xlviii <http://www.abc.net.au/news/2015-08-10/linc-energy-secret-report-reveals-toxic-chemical-risk/6681740>
- xlvi <http://www.theaustralian.com.au/business/mining-energy/linc-energy-calls-it-quits-on-ucg-project/story-e6frg9df-1226753791059>
- xlvii <http://www.ehp.qld.gov.au/management/coal-seam-gas/btex-chemicals.html>
- xlviii <http://www.atsdr.cdc.gov/toxprofiles/tp3-c6.pdf>
- xlvi <http://www.ncbi.nlm.nih.gov/pubmed/20923742>
- l <http://www.environmentalhealthnews.org/ehs/newscience/benzene-linked-to-sperm-abnormalities>
- li <http://nj.gov/health/eoh/rtkweb/documents/fs/1487.pdf>
- lii <http://www3.epa.gov/airtoxics/hlthef/phenol.html>
- liii Edris Bazrafshan, Ferdos Kord Mostafapour & Hossein Jafari Mansourian Phenolic Compounds: Health Effects and Its Removal From Aqueous Environments by Low Cost Adsorbents, *Health Scope*. 2013 July; 2(2): 65-66.
- liv <http://www3.epa.gov/epawaste/hazard/wastemin/minimize/factshts/pahs.pdf>
- lv <http://www.atsdr.cdc.gov/csem/csem.asp?csem=13>
- lvi Paulik et al., Impact of natural gas extraction on PAH levels in ambient air. *Environ Sci Technol*. 2015 Apr 21 ;49(8):5203-10. doi: 10.1021/es506095e. Epub 2015 Apr 9.
- lvii <http://www.epa.gov/iaq/voc.html>
- lviii US National Library of Medicine http://toxtown.nlm.nih.gov/text_version/chemicals.php?id=65
- lix http://toxtown.nlm.nih.gov/text_version/chemicals.php?id=19
- lx http://toxtown.nlm.nih.gov/text_version/chemicals.php?id=7
- lxi http://toxtown.nlm.nih.gov/text_version/chemicals.php?id=29
- lxii ADS Gillies, HW Wu, MS Kizil & T Harvey The Mining Challenge Of Handling Coal Seam Hydrogen Sulphide http://www.qrc.org.au/conference/_dbase_upl/2000_spk014_gillies.pdf
- lxiii https://www.osha.gov/OshDoc/data/Hurricane_Facts/hydrogen_sulfide_fact.pdf
- lxiv <http://www.who.int/mediacentre/factsheets/fs361/en/>
- lxv <http://www.who.int/mediacentre/factsheets/fs225/en/>