



*A COMMERCIAL APPLICATION OF
VIROMINE™ AND VIROFLOW™ TECHNOLOGY*

COAL MINING, COAL BENEFICATION AND COAL COMBUSTION WASTE TREATMENT

TECHNICAL PAPER



INTRODUCTION

Coal is one of the world's most plentiful energy resources, and its widespread use is likely to quadruple by 2020. Coal has a significant range of moisture contents (2-40%), sulphur contents (0.2-8%), and ash contents (5-40%); these factors affect the value of the coal as a fuel and contribute to environmental problems in its use.

Coal mining, coal beneficiation, and the combustion of coal in power plants produce several types of wastes. For example, coal mining generates solid mining waste which is a mixture of coal and rock, fine coal washery tailings which can be similar in physical and chemical composition to other mine tailings, liquid coal waste which is stored in impoundments, and acid mine drainage (AMD), sometimes referred to as acid rock drainage (ARD).

AMD-ARD is caused by the accumulation of organic matter in a waterlogged environment, which invariably leads to the establishment of anoxic and reducing conditions; coupled with an availability of sulphate and reducible iron, even at relatively low concentrations, leads to the formation of iron sulphides (mostly pyrite) that are available for oxidation and acid generation; this acid typically mobilises trace metals contained within the coal. The combination of acid and metals seeps into waterways where it can effectively sterilise many kilometres of streams, depositing substantial quantities of iron oxy-hydroxides into the environment. Coal waste rock and washery tailings are generally stockpiled on site, where they provide a suitable habitat for bacteria that accelerates the oxidation of pyrite and the production of acid. (For a more complete description of the relationship between AMD-ARD and coal mining, see Clark, McConchie, Berry, Caldicott, Davies-McConchie, and Castro, 2004). Fugitive emissions of coal dust may also occur at coal mines.

Coal beneficiation plants produce large volumes of tailings and solid wastes, and pollution control systems used for coal combustion produce fly ash, a semi-solid waste byproduct (i.e., a slurry which tends to dry out when stored for long periods), as well as furnace bottom ash and flue-gas desulfurization (FGD) blowdown wastewater, a wet semi-solid residue created by sulfur dioxide scrubbers, and flue gasses such as sulphur dioxide, nitrous oxide and carbon dioxide. Storage and handling of coal also generate dust at rates of as much as 3.0 kilograms per metric tonne (kg/t) of coal mined, with ambient dust concentrations ranging from 10-300 micrograms per cubic meter ($\mu\text{g}/\text{m}^3$) above background level at the mine site.

The World Bank (1998) has well-documented accounts of how these different forms of waste should be managed, treated and remediated, and efforts have been made to reuse these so-called coal combustion products (CCPs) in other industries, such as concrete manufacture and road construction (Ash Development Association of Australia, 1999; 2009). While the latter effort is to be generally applauded, the effective treatment of contaminants found in CCPs, which are inherited from the original fly ash or other coal waste, has at times been found wanting, with dilution of contaminants the typical method of "treating" heavy metals and radioactive elements in coal waste.



A coal fuelled power station

In all cases, the solid, liquid and gaseous wastes generated from coal mining, coal beneficiation and the combustion of coal are contaminated with a variety of pollutants, many of which are extremely hazardous and can pose a significant risk to human and environmental health; many of the indigenous contaminants in coal and liberated as a result of coal mining, coal beneficiation and coal combustion are known carcinogens, including chromium (Cr), mercury (Hg), selenium (Se) and arsenic (As); some liberated wastes also contain radioactive elements, such as uranium (U), thorium (Th), radium (Ra), lead (Pb), potassium (K), beryllium (Be), and polonium (Po), and gaseous radon (Rn), although generally only at around background levels until concentrated in industrial processes, such as coal combustion and coal ash storage. For example, an independent study of radioactive elements in solid waste from the coal combustion process has indicated that:

As expected, the fine/medium fly ashes contain higher concentrations of the volatile radionuclides, ^{210}Po and ^{210}Pb , compared to bottom ash. At the time of combustion, ^{210}Po concentrations on the finer particles will be significantly higher than those measured in this study. For example, the concentration of sample 402 (medium fly ash) was 460 Bq/kg on the counting date of 9 January 2009. This is equivalent to a concentration of 575 Bq/kg on the sampling date of 7 November 2008. If this material was produced on, say, 1 January 2008, the concentration would be 2,170 Bq/kg. Based on this assumption, the material would be considered radioactive from a regulatory perspective at the time of combustion.

It is important, therefore, that factors like this are taken into consideration. Unsupported ^{210}Po will decay and the concentration of ^{210}Po in any end-use product will ultimately be determined by the parent ^{210}Pb concentration. Polonium-210 has a half-life of 138 days and will be in equilibrium with its parent, ^{210}Pb , after approximately five half-lives, i.e. about two years. (ANSTO Minerals, 2009, p. 7)

WASTE COAL

Waste coal is a solid waste that is a byproduct of previous or current coal processing operations. Waste coal is usually composed of mixed coal, soil and rock (i.e., conventional solid mine waste). Most waste coal is burned “as-is” in fluidised-bed combustors, but for some specialty uses, waste coal may be partially cleaned by removing some extraneous noncombustible constituents and reused. Examples of waste coal include fine coal, coal obtained from refuse banks or slurry dams, and includes anthracite culm, bituminous gob, and lignite waste.

LIQUID COAL WASTE

Before burning, coal is crushed and washed, creating wastewater containing toxins. This wastewater is usually impounded and left untreated on site until evaporation and/or infiltration into groundwater systems occur. Another form of liquid coal waste is acid mine drainage (AMD), which may be collected as leachate or as surface runoff in stormwater systems. Both forms of liquid coal waste are either collected and impounded at the mine site or collected and impounded as runoff during storm events. In some cases, neither of these methods works effectively, due to the large volumes of liquid to be captured or the complexity of systems involved.

For example, in the United States each year coal mining and coal beneficiation creates wastewater containing an estimated 13 tonnes of mercury, 3,236 tonnes of arsenic, 189 tonnes of beryllium, 251 tonnes of cadmium, and 2,754 tonnes of nickel, and 1,098 tonnes of selenium. Settling ponds to catch stormwater and to reduce suspended solids in wastewater are required for effluent before discharge from coal mining sites; where treatment of AMD or other

effluents is required, the effluent concentration guidelines presented in Table 1 should be achieved during operation and after mine closure.

TABLE 1: ACID MINE DRAINAGE AND LIQUID EFFLUENTS FROM COAL MINING

Parameter	Recommended Discharge Limit
pH	6.0 - 9.0
Total Suspended Solids (mg/L)	50
Oil and Grease (mg/L)	10
Iron (mg/L)	5.0
Total metals (mg/L)	10

Example of discharge limits for treated liquid waste effluent from coal mining operations.

COAL ASH AND SCRUBBER SLUDGE

When coal is burned (i.e., combusted), toxins in the coal are released into the power plant's smokestack. With air pollution control systems, airborne toxins are captured by filtration before they can become airborne, and contained in a fine ash called coal ash, fly ash, or coal combustion waste. As a result, heavy metals such as mercury, arsenic and selenium are concentrated in what Environmental Protection Agencies generally refer to as "recycled air pollution control residues."

The more than one billion tonnes of coal burned each year in the United States contain, for example, 109 tonnes of mercury, 7,884 tonnes of arsenic, 1,167 tonnes of beryllium, 750 tonnes of cadmium, 8,810 tonnes of chromium, 9,339 tonnes of nickel, and 2,587 tonnes of selenium. On top of emitting 1.9 billion tonnes of carbon dioxide each year, coal-fired power plants in the United States also create 130 million tons of solid waste. That means each of the nation's 500 coal-fired power plants produces an average 240,000 tonnes of solid waste each year.

A power plant that operates for 40 years will therefore leave behind 9.6 million tonnes of toxic solid waste. This coal combustion waste constitutes the U.S.'s second largest waste stream after municipal solid waste (i.e., biosolids). Coal ash in the United States contains large quantities of heavy metals, including 44 tonnes of mercury, 4,601 tonnes of arsenic, 970 tonnes of beryllium, 496 tonnes of cadmium, 6,275 tonnes of chromium, 6,533 tonnes of nickel, and 1,305 tonnes of selenium generated each year.

In China, the numbers are almost beyond comprehension; with 10,000 coal-fired power plants in operation, more than 136 billion litres of FGD blowdown wastewater and 2.4 billion tonnes of toxic solid waste are generated each year (Fergusson, 2010, pp. 126-127). The same levels of solid waste are generated in India, with about 100 million tonnes of fly ash discharged into impoundments every year (Fergusson, 2010, p. 130); 13 million tonnes of fly ash are generated each year in Australia (Yunusa, Eamus, De Silva, Murray, Burchett, Skilbeck and Heidrich, 2005). As previously stated, fortunately a portion of waste fly ash generated each year by the coal combustion industry is used in the manufacture of concrete and in road construction (Ash Development Association of Australia, 1999; 2009).

AIR EMISSIONS

Fugitive air emissions also form a part of coal mining wastes. Controls are often required on individual sources of emissions, such as ventilation exhausts, if they have a significant effect on ambient particulate levels. If coal crushers or dryers are used in coal beneficiation, fabric filters or other systems are sometimes used to recover coal and reduce particulate emissions to levels below 50 mg/m³ (World Bank, 1998). Methane gas (CH₄) is also released when coal is mined. Control of methane, a greenhouse gas, to <1% by volume is required to minimize the risk of explosions in closed mines; recovery of methane is feasible when its content is > 25% by volume, but this often does not occur due to the cost of recovery.

ENVIRONMENTAL AND HUMAN HEALTH RISKS

There are a wide variety of human health and environmental risks associated with the coal mining, coal beneficiation and coal combustion industries. For example, in the United States, home to one of the world's oldest and most extensive coal mining industries, there are comprehensive and well-documented data on these risks. The following are recorded examples of accidents, types of environmental contamination, and some of the health risks arising from these industries:

- > A 2009 report claimed that the Bush Administration failed to release information which suggested an alarmingly high cancer threat to people who live near coal ash waste dump sites (Sturgis, 2009a). According to the report, the Bush Administration only made a portion of data available, hiding the true extent of the health risks associated with coal ash disposal sites. Similarly, a 2009 analysis of monitoring data from coal ash waste ponds at 13 coal plants in North Carolina was released (Sturgis, 2009b). The analysis revealed that all 13 plants in the investigation were contaminating groundwater with toxic pollutants, in some cases with over 350 times the allowable levels. The contaminants cited included heavy metals such as arsenic, cadmium, chromium, and lead, which can cause cancer and neurological disorders.
- > In 2009, the Florida Environmental Protection Agency asked the Orlando Utilities Commission to investigate the status of the ash pile from its coal plant in eastern Orange County (Spear, 2009). The EPA believed the pile was leaking radioactive elements into a shallow underground aquifer. If the uranium and radium found in the coal combustion waste was causing elevated radioactivity in groundwater, it would be a sign that the liner of the landfill had failed. The pile is 24 m tall and holds several million tonnes of solid coal ash waste.
- > In 2009, the Tennessee Valley Authority (TVA) confirmed a coal waste spill at its Widows Creek plant in northeast Alabama (Niles, 2009), less than three weeks after the enormous coal ash spill at TVA's Kingston Fossil Plant. The 2009 spill, which TVA said originated from a gypsum treatment operation, released about 10,000 gallons of toxic gypsum FGD, some of which spilled into Widows Creek and the nearby Tennessee River. Gypsum ponds contain limestone spray from FGD smokestack scrubbers, which trap sulfur dioxide emissions before they are released into the air, turning them into sludge and solid waste.
- > In the earlier 2008 coal waste accident, a retention pond wall collapsed at TVA's Kingston plant in Harriman, Tennessee, releasing a combination of water and fly ash that flooded 12 homes, then spilled into nearby Watts Bar Lake contaminating the Emory River, and caused a train wreck (White, 2008; Knoxville News Sentinel, 2008a, 2008b). TVA officials said one to two metres of material escaped from the pond to cover an estimated 400 acres

of adjacent land; a train bringing coal to the plant became stuck when it was unable to stop before reaching the flooded tracks. Hundreds of fish were found floating dead downstream from the plant, and water tests of the fly ash showed elevated levels of lead and thallium.

- > In 2010, a study published by Duke University documented the contaminant levels in aquatic ecosystems following the 2008 TVA coal ash spill (Hochenadel, 2010). When analysing more than 220 water samples collected over an 18-month period, the Duke team found that high concentrations of arsenic originating from the coal ash remained in the water trapped within river-bottom sediments long after contaminant levels in surface waters dropped back below safe thresholds. Samples extracted from 10-50 cm below the surface of the sediment in downstream rivers contained arsenic levels of up to 2,000 parts per billion, well above the EPA's thresholds of 10 parts per billion for safe drinking water, and 150 parts per billion for protection of aquatic life. The authors argued that their findings were evidence that coal fly ash waste should be designated a "hazardous" substance by the EPA.
- > TVA initially estimated that 1.7 million cubic metres of waste had burst through the storage facility, and company officials said the pond had contained a total of 2.6 million cubic metres of sludge. However, the company was forced to revise its estimate when an aerial survey showed that 5.4 million cubic metres (or 1.09 billion gallons) of fly ash was released from the storage facility; several days later, TVA's estimate was increased to over 1.0 billion gallons of fly ash was spilled. The 2008 TVA spill was 100 times larger in volume than the Exxon Valdez spill in Alaska, which released 10.9 million gallons of crude oil.
- > In 2007, residents of Gambrills, Maryland living near a former sand and gravel mine filed a class action lawsuit against Constellation Energy over contamination of their drinking water (Baltimore Sun, 2008). For twelve years, Constellation Energy had disposed of billions of tons of waste fly ash from its Brandone Shores coal-fired power plants into an unlined mine pit at the site. Tests found that 23 groundwater wells in the area had been contaminated with metals such as arsenic, cadmium and thallium, all components of the original fly ash.
- > In 2000, 250 million gallons of coal mining sludge burst through the bottom of Massey Coal's 72-acre, 2.2 billion gallon waste lagoon into Coldwater Creek in eastern Kentucky (New York Times, 2000). The sludge smashed through concrete seals the company had built to contain a spill and burst into nearby creeks; the spill swamped properties along six miles of the Coldwater Creek, coated the banks and bottom of Coldwater and neighbouring Wolf Creek to thicknesses of up to two metres, and suffocated aquatic life, including salamanders, frogs, fish and turtles. Biologists said every fish in both creeks were killed, and many in the Big Sandy River died as well. The Kentucky Division of Fish and Wildlife Resources estimated that a total of 1.6 million fish were killed.
- > In 2002, an EPA study highlighted a significant risk associated with coal fly ash sumps, but requests for data under the Freedom of Information Act were either denied or given with the estimates of cancer risk blacked out (Sturgis, 2009a). A 2007 EPA assessment report found that people living near coal fly ash dump sites have as high as a 1:50 chance of getting cancer from drinking water contaminated by arsenic; it also determined that living near such dump sites raised an individual's risk of liver, kidney, lungs and other organ damage resulting from exposure to heavy metals in the fly ash.

A report released in 2011 stated that there are many health threats associated with the cancer-causing chemical hexavalent chromium (Cr^{VI}) found in fly ash (Bayer, 2011). The report specifically cited 29 sites in 17 U.S. States where high levels of hexavalent chromium contamination were found around fly ash storage sites.

VIROTEC COAL WASTE TREATMENT TECHNOLOGIES AND OUTCOMES

For ten years, Virotec's two technologies, ViroMine™ Technology and ViroFlow™ Technology, have been used to successfully treat a wide range of solid, liquid and gaseous wastes from coal mining, coal beneficiation, and coal combustion processes. The following are a selection of global applications in which Virotec's technologies have effectively treated industrial wastes associated with coal mining, coal beneficiation and coal combustion.

Application #1: Acid Mine Drainage, Aberdare East Coal Mine, Australia

The Aberdare East Colliery is a closed underground coal mine located in Cessnock, New South Wales, 120 km north of Sydney. Coal washery tailings from the mine were impounded in a series of overlapping stacked cells in a small catchment on the site. Relatively clean water enters the south-eastern extent of the tailings and moves to the northwest down the hydrological gradient, before exiting at the north-western batter into a small creek. During passage through the tailings, salinity, metal content, redox potential, and temperature all increase, and solution pH decreases in the wastewater. Investigations indicated that the impoundment contained 109,445 m³ of liquid, 337,793 m³ of saturated fines, 720,113 m³ of unsaturated fines, and 184,568 m³ of clay capping.

Washery wastes were held adjacent to the main shaft (now sealed), a derelict coal laboratory and an area previously used for underground pit top buildings, including a coal processing plant. The washery waste area was within a site that contained rehabilitated coal products and reject dumps, old quarries, a haul road network, coal processing areas and natural bushland.

Benefits associated with the use of ViroMine™ Technology were identified as including: lowered sludge production during wastewater treatment; increased chemical stability of residues and therefore greatly reduced disposal costs; and a decreased susceptibility to dissolution of acid neutralising capacity from the soil/tailings profile that greatly reduced the likelihood of having to reapply more reagent after five or ten years and consequently a reduced safety margin for the application.

To sample the site, 19 test pits were dug and piezometers placed into the coal tailings: 18 into the coal slimes and one into the dam wall. Coal samples from the pits were analysed for pyrite content (using the chromium reducible sulphur method outlined by Sullivan, Bush, McConchie, Lancaster, Clark, Norris, Southon, and Saenger, 1998) to determine the required application rate of Virotec's chemical reagent Acid B Extra™, reaction pH, soluble acidity (see Lin, Bush, Schultz, Clark, McConchie, and Sullivan, 2000 for more details) and grain size, which indicated that the coal tailings were <2.0mm and hence referred to as "coal slimes". Water samples were taken from the seepages and analysed for pH and the following heavy metals: aluminium (Al), arsenic (As), cadmium (Cd), copper (Cu), chromium (Cr), iron (Fe), lead (Pb), manganese (Mn), nickel (Ni), and zinc (Zn).



Dam seepage at Aberdare East Colliery

TABLE 2: PRE- AND POST VIROMINE™ TECHNOLOGY RESULTS FOR TREATED ACID MINE DRAINAGE SEEPAGE AT ABERDARE EAST COAL MINE

Parameter	Untreated Seepage	Treated Seepage	Site Background Conditions	Regulatory Guildelines for Discharge
pH	2.6	8.2	7.0	6.5 - 8.5
Aluminium (mg/L)	36.9	0.03	0.006	0.1
Arsenic (mg/L)	<0.001	<0.001	<0.001	<0.001
Cadium (mg/L)	<0.001	<0.001	<0.001	<0.001
Copper (mg/L)	0.009	0.001	0.002	0.002
Chromium (mg/L)	0.008	<0.001	<0.001	0.04
Iron (mg/L)	168	0.001	0.75	No limit
Manganese (mg/L)	9.5	2.3	0.17	3.6
Nickel (mg/L)	0.65	0.008	0.002	0.17
Lead (mg/L)	<0.001	<0.001	<0.001	0.009
Zinc (mg/L)	0.68	0.002	0.006	0.03

From this data it can be concluded the application of ViroMine™ Technology to acid mine drainage seepage at Aberdare East coal mine resulted in significant reductions of all relevant metals and an increase in pH, all to within regulatory limits and all with 75-99% removal efficiencies (Clark, et al., 2004). It should be noted that researchers also concluded the application of Acid B Extra™ reagent neutralised both the total actual acidity (TAA), which was present in the coal slimes at the time of treatment, as well as the total potential acidity (TPA), which may have caused further AMD leachate in the future.



The drain at Aberdare East Colliery

TCLP analysis on the treated coal slimes indicated that the residual solids after treatment conformed to guidelines as an “inert” waste, meaning that the treated coal slimes could be disposed to regular landfill, and did not require further treatment or special disposal criteria, as shown in Table 3.

TABLE 3: TOXICITY CHARACTERISTIC LEACHING PROCEDURE ANALYSIS FOR TREATED COAL SLIMES AT ABERDARE EAST COAL MINE

Parameter	*TCLP of Treated Coal Slimes (mg/L)	Regulatory Limit for Disposal as an Inert Waste (mg/L)
Arsenic (mg/L)	<0.001	0.5
Cadium (mg/L)	<0.001	0.1
Copper (mg/L)	0.02	No limit
Chromium (mg/L)	0.07	0.5
Lead (mg/L)	<0.001	0.5
Mercury (mg/L)	<0.001	0.02
Molybdenum (mg/L)	<0.001	0.5
Nickel (mg/L)	0.13	0.2
Selenium (mg/L)	<0.001	0.1
Zinc (mg/L)	0.04	No limit

*TCLP results of treated coal slimes after treatment with ViroMine™ Technology.

Unlike lime, which leaves large volumes of chemically unstable sludge, use of ViroMine™ Technology results in the formation of a non-dispersive sediment that supports healthy plant growth; the TCLP results show that it is difficult to re-leach (i.e., desorb) heavy metals bound to sediments during water treatment. Whereas most metals removed by lime, clays and zeolites are initially adsorbed and can be desorbed if chemical conditions change slightly, most metals bound when Acid B Extra™ is used are held as structural components of minerals, are not exchangeable and are thus cannot be easily removed or re-released back into the environment. At Aberdare East coal mine, it was also found in side-by-side experiments that the amount of sludge produced as a result of applying Acid B Extra™ to treat the AMD seepage was 15 times less than that generated by the use of lime on a gram-for-gram basis.

Application #2: Acid Mine Drainage, UK Coal, United Kingdom

Virotec was commissioned to treat coal mine wastewater from Shaft No. 2 at UK Coal’s Maltby Colliery using ViroMine™ Technology. The Maltby Colliery discharges pumped mine wastewater to a surface drainage and lagoon system. The mine wastewater is contaminated with varying levels of soluble iron, which precludes discharge of water to the local watercourse. Currently, mine wastewater is recycled back for coal washing, but under certain hydraulic conditions (i.e., wet weather) the existing mine wastewater lagoons fill and threaten to overflow to an offsite discharge point, with current discharge limits of 5.0 mg/L for soluble iron (Fe) possibly being exceeded.

A ViroMine™ column flow-through configuration was specifically designed for the treatment system in which coal mine wastewater was pumped from Shaft No. 2 directly to the filter containing Acid B™ media at a controlled flow rate based on optimum retention time for Fe removal. Treated mine wastewater was discharged directly to sewer. The

column was a duty and duty/standby configuration with columns manifolded to allow switching of duty once the duty column was exhausted; pH monitoring of the treated water was used as an on-line measurement of column performance. The spent Acid B™ filter media was disposed as a mine waste on site to be used later for spoil heap remediation and revegetation.

The treatment configuration was simple, requiring no other chemical addition or equipment for sludge processing, and generated a non-leachable solid. This contrasts with the use of lime-based systems which do not meet the “Best Available Technology” requirements of the United Kingdom’s Environment Agency and have the following disadvantages:

- > For a similar system using limestone, a proportion of the limestone is spoiled because aluminium and iron/manganese-oxy-hydroxides precipitate onto the surface of limestone grains thereby reducing the system’s capacity to neutralise the coal mine wastewater;
- > Even if neutralisation of wastewater is satisfactory in such systems, metal concentrations are not always reduced to acceptably low values because metals are mostly found at high concentrations in the extractable, bio-available carbonate phase of coal mine wastewater;
- > Lime added to acidic coal mine wastewater is partially soluble and thus leached out during periods of high rainfall, together with precipitated metal hydroxides, further reducing the long-term effectiveness of the system; and,
- > Lime treatment allows temporary re-vegetation of coal tailings but is not sustainable. Liming reasonably quickly stops neutralising acid and does not prevent metals from being taken up by plants, rendering reclaimed land generally unsuitable for agricultural purposes by re-releasing metals back into the environment or into the food chain. (Work conducted separately at another mine site suggests this reversal of lime-based approaches begins within six to 12 months as opposed to a ViroMine™ Technology revegetation program which is successfully neutralising acid and promoting plant and tree growth more than eight years after application.)

These conclusions are in contrast to ViroMine™ Technology treatment and remediation which can be used to remediate metal contaminated soils and help develop a sustainable soil cover with metals fixed in a non-leachable and non-bioavailable form.

Samples of coal mine wastewater were taken over a six-week period and Fe concentrations averaged 44 mg/L (sometimes as high as 80 mg/L) and pH averaged 6.0. As a result of the ViroMine™ treatment, Fe levels were reduced to 0.5 mg/L and pH remained unchanged. When the Acid B™ media in the filter columns was tested for metal retention capacity, it was found the media bound in excess of 29 g of Fe per one kilogram of media after six weeks, with a predictive capacity of >50 g/kg.

The project concluded that ViroMine™ Technology was effective in treating Maltby Colliery wastewater over a variety of soluble metal concentrations (e.g., 20-80 mg/L) to achieve Environment Agency consent conditions or better. Assuming an average daily flow of 900 m³/day (or 137 gallons/min), ongoing treatment required a bed of 150 m³



Site of ViroMine™ Technology treatment system at UK Coal’s Maltby Colliery site

capacity containing 110 tonnes of pellets. With a trickling filter configuration the estimated bed lifetime for the system was 200 days with a treatment capacity of up to 180,000 m³ (or 40 million gallons) at an average iron concentration of 25 mg/L.

Application #3: Acid Mine Drainage, Coal Authority, United Kingdom

Virotec treated four coal AMD wastewaters with ViroMine™ Technology at four Coal Authority sites: 1) Fender coal mine water with a neutral pH of 6.5; 2) Clough Foot coal mine acid drainage with a pH of 4.2; 3) Cwmrheidol lead mine acid drainage with a pH of 3.6; and 4) Parys Mountain copper mine acid drainage with a pH of 2.6. Both direct addition and filtration systems were applied to optimise treatment outcomes, and a variety of contaminants were measured, including iron, aluminium, copper, zinc, and manganese. In all cases, acidity was effectively neutralised; for heavy metals, a range of outcomes were observed, including those presented in Table 4.

TABLE 4: VIROMINE™ TREATMENT OUTCOMES FOR FOUR COAL AUTHORITY COAL MINE SITES IN THE UNITED KINGDOM

Parameter	Before Treatment	After Treatment with ViroMine™ Technology
Fender Coal Mine		
pH	6.5	8.0
Manganese (mg/L)	1,050	<5.0
Clough Foot Coal Mine		
pH	4.2	8.5
Manganese (mg/L)	2,170	<5.0
Cwmrheidol Lead Mine		
pH	3.6	8.6
Aluminium (mg/L)	6,100	100
Iron (mg/L)	12,000	10
Zinc (mg/L)	21,000	50
Parys Mountain Copper Mine		
pH	2.6	8.0
Aluminium (mg/L)	72,000	60
Copper (mg/L)	34,000	18
Iron (mg/L)	280,000	10
Zinc (mg/L)	71,000	3,690

Acidity and heavy metal treatment outcomes for four Coal Authority coal mine sites in the United Kingdom.

The average percentage removal for metals was 99%, except zinc which was 95%. Acidity was raised slightly at Fender and effectively neutralised at the other three coal mines.

Application #4: Coal Mine Wastewater, Large Coal Mine, New South Wales, Australia

Virotec was contracted by a large coal mine to implement ViroMine™ Technology at a facility in the Hunter Valley region near Kearsley in New South Wales. The objective of the application was to treat a 5.0 ML holding and attenuation dam, primarily to reduce high iron concentrations and to raise dam pH, thereby allowing for the treated dam water to be used to wash coal tailings. The results presented in Table 5 show that ViroMine™ Technology successfully raised dam water pH to within regulatory limits, and reduced both iron and zinc to levels suitable for reuse of the dam water.

TABLE 5: PROJECT RESULTS FOR THE TREATMENT OF COAL MINE DAM WASTEWATER

Parameter	Dam Water Before Treatment	*Dam Water After Treatment	Required Limits for Water Reuse
pH	5.9	7.7	7.0 - 8.0
Iron (mg/L)	966	<0.05	2.0
Zinc (mg/L)	0.13	<0.01	NA

*Treatment outcomes as a result of applying ViroMine™ Technology to the coal mine holding dam water.



The holding dam which was treated by ViroMine™ Technology at a large coal mine in New South Wales, Australia



The Virotec operations team pumping contaminated holding dam water to the treatment facility (rear)

Application #5: Coal Mine Wastewater, Large Coal Mine, Queensland, Australia

A large coal mine in central Queensland commissioned Virotec to deploy its ViroMine™ Technology in both a direct addition and permeable reactive barrier (PRB) configuration to treat on-site acidic mine wastewater. The direct addition of Acid B Extra™ resulted in the following treatment outcomes presented in Table 6, which show that the addition of Acid B Extra™ resulted in a significant increase in pH and a significant reduction in all target heavy metals to within regulatory discharge limits.

TABLE 6: RESULTS FOR THE TREATMENT OF ACIDIC COAL MINE DAM WASTEWATER IN QUEENSLAND USING DIRECT ADDITION

Parameter	Dam Water Before Treatment	Dam Water After Treatment	Discharge Limits
pH	2.9	5.8	5.0 - 9.0
Aluminium (mg/L)	34.3	<0.05	5.0
Manganese (mg/L)	30.5	1.7	No limit
Nickel (mg/L)	0.43	<0.02	No limit
Zinc (mg/L)	1.5	0.01	No limit

The option of using PRBs to treat AMD at coal mine sites has the potential advantage that well-designed barriers can be constructed and left unattended, but there are challenges with designing barriers that work effectively over the long term. Designing PRBs that do not develop preferential flow pathways (piping or tunnelling) is testing, with the main challenge lying with the selection of suitable reactive materials for use in the construction of the PRB. For extremely acidic water (pH <2.5), olivine-rich rocks can be used to form cheap PRBs, but they cannot raise pH or reduce the metal content of wastewater sufficiently, and thus they can really only be used as a first-stage treatment option.

Limestone (or similar materials, such as magnesium carbonate) has been widely used to form PRBs, but there are many problems with its use (Evangelou and Zhang, 1995; Powell and Blowes, 1998; Evangelou, 1998), including:

1. reaction between lime and sulphate forms gypsum that blocks pore spaces and progressively reduces the hydraulic conductivity of the barrier;
2. aluminium- and iron-oxyhydroxides, that precipitate as the lime neutralises acid, coat lime particles and prevent them from continuing to neutralise water;
3. lime is slightly soluble and can be leached out in high rainfall areas before all acid has been neutralised; and,
4. lime barriers seldom reduce metal concentrations to acceptably low values.

Anoxic limestone drains (Titchenell and Skousen, 1996; Skousen and Sexstone, 1999) were developed in an attempt to solve the problems caused by iron-oxyhydroxide precipitation, but they cannot prevent aluminium hydroxide precipitation and they do not overcome the other problems associated with the use of lime; it is also very difficult to ensure that anoxia is maintained in the drains. Many anoxic limestone drains fail within a few months of construction, and very few continue to operate effectively for more than two or three years.

Acid B Extra™ can be used to form PRBs that will neutralise acid and strip trace metals from contaminated water without impeding water flow. These types of PRBs can be constructed using porous pellets or blocks prepared or by mixing Acid B Extra™ with sand, soil or crushed rock which might be available on site. The design and dimensions of each PRB need to be carefully determined to provide a balance between hydraulic retention time (i.e., reaction time in the barrier or filter) and the barrier permeability required to handle flow rate and volume of the water to be treated.

PRBs designed for use in ViroMine™ Technology have several advantages over PRBs constructed using limestone, including:

1. they can be used with fully oxygenated water;
2. iron and aluminium are largely removed by crystal growth on iron-oxides and aluminium-hydroxides present in Acid B Extra™ rather than by precipitation of oxyhydroxide coatings on particles that need to remain in contact with the water;
3. the formation of gypsum does not adversely affect permeability;
4. minerals in Acid B Extra™ have a low solubility and are not lost during high rainfall; and,
5. metal concentrations in water passing through the PRB are acceptably low; and,
6. PRBs constructed using ViroMine™ Technology support healthy plant growth and can be revegetated while still in use.

PRBs constructed for use in ViroMine™ Technology have demonstrated that their permeability remains roughly constant from the time the first water is passed through them until the limit of their water-treating capacity is reached. As with all PRBs, there is a limit to their capacity to effectively treat water at which point they need to be replaced. However, unlike PRBs formed using limestone or other materials, metals bound to the minerals in Virotec's PRBs remain tightly held, and if the barrier needs to be removed or replaced, the spent media can be spread on land elsewhere on the site and revegetated. Alternatively, the exhausted material in the PRB may simply be left where it is and revegetated, with a new PRB being placed beside it.

Virotec designed and utilised a PRB to treat the wastewater from the large coal mine in Queensland in order to test its effectiveness in treating contaminated coal mine wastewater and the results of treatment are presented in Table 7. From these data it can be seen that the PRB was effective in raising pH and reducing aluminium concentrations in the wastewater.

TABLE 7: RESULTS FOR THE TREATMENT OF COAL MINE DAM WASTEWATER USING A PERMEABLE REACTIVE BARRIER FILTRATION SYSTEM

Parameter	Dam Water Before Treatment	Dam Water After Treatment	Discharge Limits
pH	2.9	7.3	5.0 - 9.0
Aluminium (mg/L)	34.3	<0.03	5.0

Before and after results for the treatment of acidic coal mine wastewater at a large coal mine in Queensland using a PRB.

Application #7: Flue Gas Desulfurisation Blowdown, Progress Energy, South Carolina

At a Progress Energy power plant in South Carolina, ViroFlow™ Technology was applied to FGD blowdown wastewater. The primary focus of the application was to treat the arsenic and chromium contamination in the FGD blowdown wastewater, a major problem for most power plants in the U.S. Two direct addition treatments were demonstrated and the results are presented in Table 8. A more comprehensive description of flue gas desulfurisation blowdown and its effective treatment is provided in Virotec's Technical Paper "Coal-Fired Power Plant Wastewater Treatment".

TABLE 8: RESULTS OF TREATING FLUE GAS DESULFURISATION BLOWDOWN WASTEWATER USING VIROFLOW™ TECHNOLOGY

Parameter	Arsenic (µg/L)	Chromium (µg/L)	Iron (µg/L)
Untreated FGD Blowdown Wastewater	200	5.16	21.60
FGD Blowdown Wastewater After ViroFlow™ Technology Treatment #1	0.25	0.44	6.29
FGD Blowdown Wastewater After ViroFlow™ Technology Treatment #2	0.31	0.54	6.60
Regulatory Limits for FGD Blowdown Wastewater	1.0	1.0	15

Treatment targets and results at the South Carolina power plant FGD blowdown wastewater in parts per billion.

From the data presented in Table 8, it can be seen that Treatments #1 and #2 both met all discharge limits for treated FGD blowdown wastewater prior to discharge into a nearby river with U.S. EPA approval.

Application #8: Coal Rolling Stock Washdown Wastewater, Queensland Rail, Australia

Virotec was contracted by Queensland Rail to implement ViroFlow™ Technology to treat industrial wastewater at the Jilalan Rolling Stock Maintenance Depot. The Jilalan Rolling Stock Maintenance Depot, the site of cleaning rolling stock carrying coal from the Bowen Basin to ports on the east coast of Australia, had not been able to meet its EPA discharge requirements for copper, phosphorous, BOD, and suspended solids in coal washdown wastewater over many years of operation. Facing further reductions in discharge limits to come into effect, Queensland Rail decided to look for a solution to their washdown wastewater compliance issues. In addition, Queensland Rail had on-going problems with sludge management and disposal. The washdown wastewater to be treated was mildly acidic, with an initial pH of 5.0 and a high metal content, particularly copper, iron, and aluminium, and high suspended solids, BOD and phosphorus.

ViroFlow™ Technology was successful over a five-year period in meeting all EPA discharge limits. Following treatment using ViroFlow™ Technology, the treated effluent showed a significant improvement in water clarity and colour. Queensland Rail personnel also commented that the objectionable odour was significantly less in relation to the

odour after standard treatment. This outcome was expected because other applications had previously indicated that ViroFlow™ Technology reagents have excellent odour-reducing properties. Queensland Rail personnel also commented on the clarity of the treated water, stating that it was as “clean as they had ever seen”. In addition to improving the appearance and smell of the effluent, treatment using ViroFlow™ Technology reduced concentrations of all metals in the water to well below applicable water quality targets.

TABLE 9: RESULTS OF TREATING COAL ROLLING STOCK WASH-DOWN WASTEWATER USING VIROFLOW™ TECHNOLOGY

Parameter	Before Treatment	After Treatment	EPA Discharge Limits
pH	6.5	6.7	6.5 - 8.5
Copper (mg/L)	0.54	0.03	0.1
Total Phosphorus (mg/L)	10	0.23	2.0
Total Suspended Solids (mg/L)	53	3.0	30
Oil and Grease (mg/L)	29	<2.0	10
BOD (mg/L)	201	6.0	20
Odour	High	No Odour	No Odour

NATA-certified treatment results for coal washdown wastewater at Queensland Rail’s wastewater plant.

Currently sludge generated from the treatment plant is transported long distances to a suitable regulated landfill. A significant benefit in using ViroFlow™ Technology is its ability to reduce leachable metal levels in treated solid waste such that the solids may be disposed to local, general-purpose landfills. After ViroFlow™ Technology had been in place at Jilalan Wastewater Treatment Plant for a month, the resultant sludge was sampled, analysed and compared to the EPA guidelines. The results of this analysis are presented in Table 10.



The Virotec Dosing Plant at Jilalan Rolling Stock Maintenance Depot

TABLE 10: VIROFLOW™ TREATMENT OUTCOMES FOR COAL WASHDOWN WASTEWATER

Parameter	TCLP of Treated Sludge (mg/L)	Allowable TCLP Limits (mg/L)
Arsenic	0.008	0.5
Cadmium	0.007	0.05
Chromium	0.05	0.5
Copper	7.6	10
Nickel	0.2	0.5
Lead	0.002	0.5
Mercury	0.001	0.01
Selenium	0.001	0.1
Zinc	1.2	50

Treated sludge quality results for solids generated from coal washdown wastewater treatment.

The results in Table 10 indicate the suitability of ViroFlow™ Technology to treat sludge to within acceptable limits, allowing it to be accepted into general-purpose, clay-lined landfills. This resulted in considerable cost savings for Queensland Rail, as the treated sludge was disposed to a local landfill rather than being hauled a long-distance to a regulated landfill.

Application #9: Flue Gas Scrubbing, U.S. EPA, California, USA

In 2003, a study of the possible use of ElectroBind™ reagent to treat flue gasses emanating from a coal-fired power plant was initiated by the stack emissions gas treatment testing facility of the U.S. EPA Office of Research and Development to determine whether ElectroBind™ reagent could remove acid-forming gasses (e.g., sulphur dioxide), mercury vapour and/or any other volatile contaminants.

The study began as an investigation into the possible use of ElectroBind™ reagent to prevent the escape of potentially acid-forming gasses. The results showed that while ElectroBind™ reagent was not entirely successful in treating acid-forming gasses in FGD, it did remove substantial quantities of mercury vapour, which was not an outcome that could be achieved by alternative treatments. Results of this study are presented in Table 11.

TABLE 11: RESULTS OF FLUE GAS SCRUBBING OF COAL-FIRED POWER PLANT EMISSIONS OBTAINED BY THE U.S. EPA

Temperature (°C)	Mercury Removed (µg/L)	Mercury Removal (%)	Mercury Captured (µg/L)	Mercury Captured (%)	Mercury Oxidised (%)
40	58.6	97.0	25.4	42.1	54.9
80	35.2	58.2	25.0	41.4	16.7
140	50.8	84.1	12.4	20.6	63.5

Mercury removal from flue gasses generated by a coal-fired power plant in California using ElectroBind™ reagent

The analytical equipment used in this study only measured vapour-phase elemental mercury but missed any mercury that had been oxidized to the Hg²⁺ state (likely as HgCl₂). However, because the facility knew the amount of mercury injected into the FGD-ElectroBind™ vapour chamber, the amount of elemental mercury which came out of the chamber, and the amount and percentage captured, the facility could determine the exact amount of mercury oxidized by difference; the Hg mass balance was therefore: Hg(total in) = Hg(elemental out) + Hg(captured) + Hg(ionic out). As a result, the U.S. EPA proposed that it was now possible to use the expression “Hg removal” rather than “Hg capture” or “Hg adsorption”, because solids analysed indicated that both the binding/capturing of heavy metals in gasses as well as the catalytic oxidation of heavy metals in gasses was taking place as a result of the injection of ElectroBind™ into FGD gasses.

The U.S. EPA Office of Research and Development noted that the 40°C case was special because by using ElectroBind™ reagent they were able to remove 97% of mercury (42% by the adsorption of elemental mercury onto the solids and 55% oxidized). At 80°C they had about 60% removal with only 17% due to oxidation, whereas at 140°C the removal efficiency had risen to 84% and about 64% of this removal involved oxidation. These observations led the U.S. EPA Office of Research and Development to conclude that there must be two competing mercury removal mechanisms involved in the removal and binding process when ElectroBind™ is used; a) physiosorption that is more favourable at lower temperatures, and b) catalysed oxidation of Hg (elemental) to Hg²⁺, which is favoured at higher temperatures.

Application #10: Flue Gas Scrubbing, United Kingdom

Virotec announced the results of trials held in the United Kingdom by Newcastle-based Graphite Resources Limited conducted in 2010. Graphite Resources measured the effects of Virotec’s ElectroBind™ reagent to reduce volatile organic compounds (VOCs) in gas emissions which mimic those from the coal-fired power plant. The independent trials demonstrated that ElectroBind™ was effective in reducing the level of VOCs in gaseous emissions from 730 parts per million down to 140 parts per million, an 81% reduction. The results were obtained by passing the gaseous emissions through a ViroFlow™ Technology filtration system.

Volatile organic compounds are organic chemical compounds which exist at specific vapor pressures and which can affect the environment and human health. VOCs are numerous, varied, and ubiquitous. Although VOCs include both man-made and naturally occurring chemical compounds, it is the anthropogenic or man-made VOCs that are of the greatest concern and which are the most tightly regulated. Volatile organic compounds are typically not acutely toxic, but have chronic effects.

Emissions of VOCs, such as benzene from oil refineries and chemical plants, from coal-fired power plants pose a long-term health risk to workers and local communities. In situations where large amounts of flammable liquids and gases are contained under pressure, fugitive emissions also increase the risk of fire and explosion. Volatile organic compounds include aliphatic hydrocarbons, ethyl acetate, glycol ethers, and acetone. Many building materials, such as paints, adhesives, wall boards, and ceiling tiles, slowly emit formaldehyde, which irritates the mucous membranes, and VOCs including formaldehyde are often found in the fugitive emissions of power plants.

Some of the health effects caused by exposure to VOCs include eye, nose, and throat irritation, headaches, loss of coordination and nausea, and damage to the liver, kidneys, and central nervous system. Some VOCs cause cancer in animals and some are suspected or known to cause cancer in humans. The ability of VOCs to cause adverse health effects varies greatly from those that are highly toxic to those with no known health effects.

Application #11: Greenhouse Gas Scrubbing, United Kingdom

Virotec's gas scrubbing technology has also been investigated in United Kingdom by an independent research company, Aqua Enviro. Aqua Enviro conducted a treatability study to examine the gas generation from a liquid waste to determine its anaerobic digestion properties and to determine whether a ViroFlow™ Technology filter system would be effective in reducing gas contaminants, and also to compare the removal efficiencies of a ViroFlow™ Technology filter with a filter system containing activate carbon.

The liquid waste was pumped through a pilot scale Up-flow Anaerobic Sludge Blanket (UASB) where the carbon and nitrogen contained in the liquid are converted into gas using an attached growth biomass on granular sludge. The gas was composed of carbon dioxide (CO₂), methane (CH₄) and hydrogen sulphide (H₂S). While H₂S is not commonly associated with coal combustion but with general industrial gas emissions, carbon dioxide and methane are primary coal-based industry gasses, which are routinely emitted and/or scrubbed after coal combustion.

TABLE 12: RESULTS OF TREATING GREENHOUSE GAS EMISSIONS USING VIROFLOW™ TECHNOLOGY

Parameter	Before Treatment (mg/L)	After Treatment (mg/L)	Percent Removals (%)
ViroFlow™ Technology			
Methane	73.1	0.4	99
Carbon Dioxide	24	0.1	99
Hydrogen Sulphide	1,058	145	95
Activated Carbon			
Methane	64	6.5	90
Carbon Dioxide	17.7	2.9	84
Hydrogen Sulphide	61	11	82

Results of treating common emissions found in flue gasses from coal-fired power plants.

The ViroFilter™ Technology treatment system, composed of Virotec's ElectroBind™ chemical reagent, was dried and sealed in a measuring cylinder and a PVC tube attached to the gas cylinder from the UASB; the gas composition is measured on the inlet to the cylinder and then drawn through the media using a vacuum gas analyser to measure the gas composition at the outlet of the cylinder.

Table 12 presents the inflow and outflow results of the ViroFlow™ Technology gas treatment; these are compared to the results obtained from treating a similar gas using activated carbon as the filter media. As can be seen from the results in Table 12, ElectroBind™ media removed in excess of 99% of CH₄ and CO₂ and approximately 90% of available H₂S. These removal rates compared favourably with the removal efficiencies of activated carbon, a more widespread but costly filter media for flue gas scrubbing, which removed 90% of CH₄, 84% of CO₂, and 82% of H₂S.

The conclusion drawn from this data is that ViroFlow™ Technology has the ability to significantly reduce some of the contaminated greenhouse gasses commonly emitted from coal-fired power plants in the combustion of coal, and that it is expected that the Technology would have a similar ameliorating effect when treating sulphur dioxide (SO₂), nitrous oxide (N₂O), and other greenhouse gasses emitted from the combustion of coal.

CONCLUSIONS

From this data it is reasonable to conclude that Virotec's two technologies—ViroMine™ Technology, applied in coal mining and coal beneficiation waste treatments, and ViroFlow™ Technology, applied in coal combustion waste treatments—have a great deal to offer the coal mining, coal beneficiation and coal combustion industries, and therefore have a significant role to play in protecting the environment and communities. Any of the accidents or larger scale disasters listed herein are a warning to the coal mining, coal beneficiation and coal combustion industries that the utmost care needs to be taken when handling coal, and when disposing or discharging its waste streams into the environment.

In addition to being effective methods of treating the common contaminants found in solid, liquid and gaseous coal wastes, these two Virotec technologies have proven over ten years to also be cost-effective and environmentally sustainable, as the costs for implementing the solutions are competitive and do not adversely affect the environment or workers; they are safe to handle and do not pose a risk to humans or the environment. The technologies therefore provide a long-term, sustainable solution to the treatment of the ever-increasing, large-scale volume of waste that is being generated by the world's coal-burning, fossil-fuel based industries and economies.

REFERENCES

- ANSTO Minerals (2009). *Assessment of Naturally Occurring Radionuclides in Australian Coal Combustion Products (CCPs)*, ANSTO Minerals, Menai, NSW, Australia, Technical Memorandum: AM-TN-2009-03-06, April 19, 2009.
- Ash Development Association of Australia (1999). *Controlled Low Strength Material in Road Construction*, Ash Development Association of Australia, Reference Data Sheet No. 3, 1999.
- Ash Development Association of Australia (2009). *Post-tensioned Structural Fly Ash Concrete*, Ash Development Association of Australia, Reference Data Sheet No. 9, 2009.
- Baltimore Sun (2008). Constellation, Gambrills Residents Settle Fly-ash Suit, *Baltimore Sun*, November 1, 2008.
- Bayer, A. (2011). Coal ash waste tied to cancer-causing chemicals in water supplies, *Examiner.com*, February 1, 2011.
- Clark, M., McConchie, D., Berry, J., Caldicott, W., Davies-McConchie, F. and Castro, J. (2004). Bauxsol Technology to Treat Acid and Metals: Applications in the Coal Industry. In J. Skousen and T. Hilton (Eds.), proceedings of the joint conference the *American Society of Mining and Reclamation and the 25th West Virginia Surface Mine Drainage Task Force*, Morgantown, WV, April 18-24, 2004, pp. 292-313.
- Evangelou, V.P. (1998). *Environmental Soil and Water Chemistry: Principles and Applications*, New York, USA, John Wiley and Sons, 1998.
- Evangelou, V.P. and Zhang, Y.L. (1995). A Review: Pyrite Oxidation Mechanisms and Acid Mine Drainage Prevention, *Critical Reviews in Environmental Science and Technology*, 1995, 25, 141-199.
- Fergusson, L. (2010). *Virotec: A Ten-year Story of Success in Environmental Remediation*, Queensland, Australia, Prana World Publishing, 2010.
- Hoehenadel, D. (2010). Coal Ash Contamination Lingers in Sediment, Duke Researchers Find, *Lake Scientist*, November 30, 2010.
- Knoxville News Sentinel (2008a). Ash Spill: TVA Triples Amount of Sludge Released, *Knoxville News Sentinel*, December 26, 2008.
- Knoxville News Sentinel (2008b). Lead and Thallium Taint Water Near TVA Pond Breach, *Knoxville News Sentinel*, December 26, 2008.
- Lin, C., Bush, R.T., Schultz, J., Clark, M.W., McConchie, D. and Sullivan, L. (2000). Acid Removal and Sulphate Retention by Seawater-neutralised Bauxite Refinery Residues (Red Mud). Paper presented at *The 5th International Symposium on Environmental Geochemistry*, Capetown, South Africa, April 2000, Abstracts Volume, p. 94.
- New York Times (2000). A Torrent of Sludge Muddies a Town's Future, *New York Times*, December 25, 2000.

Nilles, B. (2009). Coal Waste Spills by the Dozen, *Daily Kos*, January 9, 2009.

Powell, R.M. and Blowes, D.W. (1998). Permeable Reactive Barrier Technologies for Contaminant Remediation, EPA/600/R-98/125, Washington, D.C., United States Environment Protection Agency, 1998.

Skousen, J.G. and Sexstone, A.J. (1999). Acid Mine Drainage Treatment with a Combined Wetland/anoxic Limestone Drain: Greenhouse and Field Systems. Presented at the *National Meeting of the American Society for Surface Mining and Reclamation*, Scottsdale, Arizona, American Society for Surface Mining and Reclamation, 1999.

Spear, K. (2009). Fears Mount on How OUC Handles Ash from Coal Plant, *Orlando Sentinel*, January 25, 2009.

Sturgis, S. (2009a). Bush Administration Hid Coal Ash Dumps' True Cancer Threat, *Instituted for Southern Studies*, May 8, 2009.

Sturgis, S. (2009b). All North Carolina Coal Ash Ponds are Leaking Toxic Pollution to Groundwater, *Institute for Southern Studies*, October 7, 2009.

Sullivan, L.A., Bush, R.T., McConchie, D., Lancaster, G., Clark, M.W., Norris, N., Southon, R. and Saenger, P. (1998). Chromium Reducible Sulphur: S_{Cr}-Method 22B, Miscellaneous Research Methods, in Y. Stane, C.R. Ahern, and B. Blunden (Eds.), *Acid Sulfate Soil Manual*, Wollongbar, Acid Sulfates Soils Management Advisory Committee, 1998, p. 9/1-9/4.

Titchenell, T. and Skousen, J.G. (1996). Acid Mine Drainage Treatment in Greens Run by an Anoxic Limestone Drain. In J. G. Skousen and P. F. Ziemkiewicz (Eds.), *Acid Mine Drainage Control and Treatment*, Morgantown, West Virginia, West Virginia University and the National Mine Land Reclamation Center, 1996, pp. 345-356.

Yunusa, I.A.M., Eamus, D., De Silva, D.L., Murray, B.R., Burchett, M.D., Skilbeck, G.C., and Heidrich, D. (2005). *Prospects for Coal-ash in the management of Australian Soils*. Paper presented to 2005 World of Coal Ash, Lexington, Kentucky, USA, April 11-15, 2005.

White, C. (2008). Dike Bursts, Floods 12 Homes, Spills into Watts Bar Lake, *Knoxville News Sentinel*, December 22, 2008.

World Bank (1998). *Pollution Prevention and Abatement: Coal Mining*, Draft Technical Background Document, Environment Department, Washington, D.C., USA.

Some of the text and images in this Technical Paper are used under a Creative Commons Deed and “fair use” under U.S. copyright law, and are not held as copyright by Virotec Global Solutions. For information on the Creative Commons Attributions—Share Alike License, please refer to <http://creativecommons.org>; this site provides details of the terms and conditions under which these text and images have been used by Virotec Global Solutions.