12th U.S./North American Mine Ventilation Symposium 2008 – Wallace (ed)
ISBN 978-0-615-20009-5

Thermal oxidation of coal mine ventilation air methane

J. M. Somers
U.S. Environmental Protection Agency, Coalbed Methane Outreach Program, Washington, DC, USA

H. L. Schultz
BCS, Incorporated, Laurel, Maryland, USA

ABSTRACT: Methane is a powerful greenhouse gas and the principal component of natural gas. Coal seams often contain significant quantities of methane, and underground coal mines must ensure that methane released into the mine during coal extraction does not build to dangerous levels. This is accomplished in part through the use of large-volume ventilation systems that remove methane from the mine and release it to the atmosphere. Although the methane concentration exhausted is quite low (typically <1 percent), the volume of air that ventilation systems move is so great that they actually constitute the largest source of methane emissions from underground coal mines. Each year underground coal mines throughout the world emit more than 500 billion cubic feet of methane from their ventilation systems. An air pollution control technology, thermal oxidation using a flow-reversal reactor (TFRR), has emerged as a potential solution to ventilation air methane (VAM) emission mitigation. One manufacturer of TFRRs has demonstrated its oxidizer design (the VOCSIDIZER™) at coal mines in the United Kingdom and Australia. These demonstrations tested the technology's effectiveness at oxidizing low-concentration methane, as well as its ability to tap the excess heat to produce steam for electric power generation. In early 2007, the first U.S. demonstration of this technology began operation at an abandoned mine in West Virginia. The project is designed to prove the technology's operational robustness, its ability to reliably oxidize methane at concentrations typical of mine exhausts, and its safety. If the technology is employed at active underground coal mines, it offers the potential to mitigate substantial quantities of global methane emissions. This paper discusses global VAM emissions, options for the recovery and utilization of VAM, and existing projects such as WestVAMP in Australia and the ongoing U.S. VAM demonstration project.

1 Introduction

Methane (CH_4) released to the atmosphere from gassy underground coal mine ventilation systems constitutes a major source of greenhouse gas emissions. As concern over climate change grows worldwide, mitigating ventilation air methane (VAM) emissions is drawing increasing attention. Field demonstrations of VAM oxidation technology in the United Kingdom, Australia, and the U.S. have paved the way for the emergence of a new industry focused on capturing the energy embodied in VAM exhaust flows and putting it to beneficial use. With supplemental revenues potentially available from domestic and international carbon funds, the economics of VAM emission mitigation appear favorable. As a result, interest in implementing VAM emission mitigation technology in the U.S. and elsewhere is growing rapidly.

Methane is formed over geologic time as the coalification process converts organic material into coal, and may be present both in coal seams as well as in adjacent rock strata. Deep underground coal mines may encounter substantial reservoirs of methane. Methane is released into the mine environment as coal is extracted, unless it has been removed prior to mining through the application of gas drainage techniques. Deep longwall operations, which are characterized by high extraction rates of often very gassy coal, can release substantial amounts of methane. This could constitute a dangerous situation since methane, the principal component of natural gas, is explosive at concentrations ranging from 5 to 15 percent in air.

Coal mines are required to manage methane concentrations underground so that they do not approach the lower explosive limit of 5 percent, in order to ensure a safe environment for mine workers. In the U.S., if methane concentrations reach 1 percent in mine workings, specific response actions must be taken (per CFR 75.323 – *Actions for Excessive Methane)*, which can be disruptive to mine productivity. Therefore, controlling methane in deep, gassy underground coal mines is an ongoing concern for mine operators, both in terms of ensuring worker safety as well as maximizing coal production and profitability.

Two methane management approaches are available for gassy underground coal mines. Large-scale ventilation systems are employed to bring fresh air into the workings, where they dilute methane released during coal extraction and expel it from the mine into the atmosphere. At very gassy mines, however, the cost of operating a ventilation system large enough to handle high methane release rates can be cost prohibitive. In such circumstances, gas drainage can be employed to supplement the ventilation system. Drainage involves drilling boreholes into the coal seam (from the surface or within the mine), through which methane can be extracted from the coal before it is mined, or into the gob zone. Gob (or goaf) is the rubble area of broken rock that forms when the mine roof collapses as the longwall equipment advances during mining. Gob gas often continues to be released for extended periods after mining.

Gas drainage typically produces methane ranging from medium to high quality. This gas is suitable for a number of beneficial uses, including natural gas pipeline injection and electric power generation fuel. In contrast, VAM usually exits the mine at concentrations below 1 percent. However, because the air flow of coal mine ventilation systems is so large,[1] the total amount of methane that exits those systems typically exceeds that released from drainage systems (see Figure 1). In 2005, ventilation systems contributed 54 percent to total methane emissions from coal mines in the U.S.

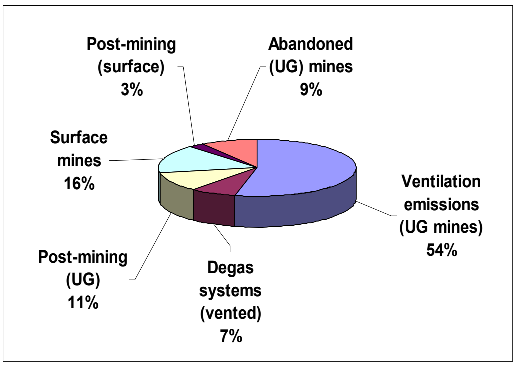

Figure 1. Sources of U.S. Coal Mine Methane Emissions in 2005

In addition to posing a safety hazard, methane also is a powerful greenhouse gas (GHG), with a global warming potential (GWP) over 20 times that of carbon dioxide.[2] This fact, in combination with the magnitude of VAM emissions, highlights VAM emission mitigation as a particularly important element of an integrated approach to addressing the causes of climate change. Using the energy content of VAM would constitute a beneficial means of mitigating its release to the atmosphere. In contrast to drained gas, however, the combination of high flow volumes carrying low concentrations of methane poses significant challenges to VAM capture and use.

In a past field demonstration at the Appin Colliery in Australia, the energy content of VAM was captured by using it as combustion air in a bank of internal combustion engines generating electricity. In that application, VAM was used as a supplemental energy source. Efforts to develop technologies capable of using VAM as the primary power source (e.g., lean-fuel turbines) also have been pursued. In recent years, a technology has emerged capable of oxidizing VAM: flow-reversal oxidation. Employed safely and effectively at hundreds of industrial locations worldwide for volatile organic compound (VOC) emission control, the technology has been demonstrated to oxidize VAM at abandoned and active coal mines. It is currently being used to power electricity generation at an active mine in Australia. The United States Environmental Protection Agency (USEPA, 2003) estimated that in 2002 full (upper bound) deployment of VAM oxidation technology for power generation applications at gassy mines in the U.S. alone could mitigate 25.8 million tonnes CO_2e (1.8 Bm^3 methane) and produce \$1.2 billion in equipment sales and \$124 million in electricity sales each year. These Figures were based on VAM emission estimates and an assumed carbon emission reduction revenue price of \$3.00 per tonne CO_2 equivalent (CO_2e).[3] The USEPA study also estimated VAM emissions for the two largest emitters, China and the U.S., at 6.7 Bm^3 and 2.6 Bm^3, respectively. Australia's emissions in 2002 were estimated at 0.7 Bm^3. The mitigation of these large volumes of methane emissions would clearly result in significant environmental benefits, in addition to the economic benefits cited above.

2 Flow-Reversal Oxidation – Operating Principals

The basic operating principal underlying flow-reversal regenerative oxidizers is rather straightforward. Each oxidizer unit comprises a bed of heat exchange material with a preheating system (e.g., electric heating element). Ducting conveys the gas to be oxidized (VAM in this case) into the oxidizer core. The heat exchange material typically comprises ceramic pellets with a high surface area-to-volume ratio. The oxidizer also has a system of valves and dampers that direct the VAM flow across the bed. To start up the system, the preheating system raises the temperature of the heat exchange material in the oxidizer bed to or above the auto-oxidation temperature of VAM (1,000°C or 1,832°F), at which point the preheating system is turned off and VAM inflow is initiated. The methane oxidizes when it reaches the preheated bed, releasing the heat of combustion. This heat, in turn, is transferred to the bed, thereby maintaining its temperature at or above the temperature necessary to support auto-thermal operation. It should be noted that the oxidation process is flameless and, following the initial bed preheating, requires no auxiliary fuel so long as adequate inflow methane concentrations are maintained (hence the term regenerative).

[1] In the U.S., typical underground mines release from 212,000 to 530,000 cubic feet per minute, or ~100 to 250 cubic meters per second, of ventilation exhaust air.

[2] The Intergovernmental Panel on Climate Change's Third Assessment Report (2001) cites a GWP for methane of 23 times that of CO_2 (the reference greenhouse gas). This is on a mass-basis over a 100-year time frame.

[3] \$3.00 per tonne CO_2e was a reasonable value at the time of the study. Since that time, however, the global carbon markets have matured somewhat and sale prices as high as \$20.00 per tonne have been reported for CMM emission mitigation (see Hamilton et al., 2007).

However, if the inflow of ambient-temperature ventilation exhaust air is maintained in only one direction, the heated area of the bed would migrate across the bed in the direction of flow until the heat essentially is blown out of the bed. If that happens, bed temperatures would no longer be adequate to sustain auto-thermal operation, and the system would cease oxidizing subsequent VAM inflows. To preclude cooling of the bed, dampers and valves redirect the flow of incoming ventilation exhaust air from one side of the bed to the other, typically on a timeframe of every two or three minutes (see Figure 2). This flow-reversal process, which is managed by a programmable logic controller, maintains the hot area of the bed in the middle of the oxidizer, where it is available to support oxidation of a constant stream of VAM over time.

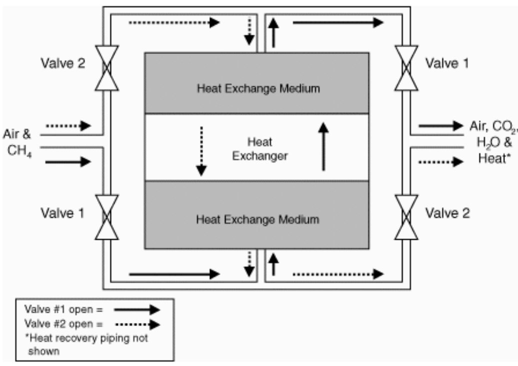

Figure 2. Schematic of Thermal Flow-Reversal Reactor

Flow-reversal oxidizers can be of two types: thermal or catalytic. The operating principal is the same, the only difference being that a catalyst is added to the oxidizer core, thereby lowering the auto-oxidation temperature and reducing the temperature at which the equipment must operate. The temperature-lowering benefit comes at a cost, however, since the catalyst is an added component not included in a basic thermal flow-reversal design. Also, the potential of contaminants in the ventilation exhaust stream to poison[4] the catalyst must be considered before use in VAM oxidation applications.

3 Flow-Reversal Technology Demonstrations and Commercial-Scale Implementation

Only one oxidizer manufacturer, MEGTEC Systems of DePere, Wisconsin, has demonstrated their technology (the VOCSIDIZER™)[5] on a commercial scale using VAM. The Canadian CANMET Energy Technology Centre in Varennes, Canada has adapted flow reversal technology and developed a prototype catalytic flow reversal for VAM applications called the CH_4MIN. Further development and deployment of their design is contingent on a licensee moving it into a field application. Another TFRR system designer, Biothermica Technologies, Inc. of Montreal, Canada, has begun to explore the application of its Biotox oxidizer system in VAM applications. Like MEGTEC, their design has been used successfully in industrial VOC and also condensable organic compound emission control applications. Other technology developers, such as Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO), Energy Developments Limited, FlexEnergy, and Ingersoll-Rand, have been pursuing development of lean fuel turbines capable of running on methane concentrations as low as 1.0 percent. In addition, CSIRO also demonstrated a hybrid rotary kiln/turbine system that runs on waste coal and VAM.

With hundreds of oxidizers in operation at industrial VOC control sites, MEGTEC began to demonstrate the efficacy of their TFRR technology in VAM oxidation applications in the late 1990s. The VOCSIDIZER™ technology was first demonstrated in 1994 at British Coal's Thoresby Mine in Nottinghamshire, United Kingdom. This project successfully demonstrated the TFRR's ability to maintain efficient, sustained operation on mine exhaust flows.

Following the success of the initial demonstration, MEGTEC's TFRR was further demonstrated at the Appin Colliery in New South Wales, Australia in 2001-2002. The Appin demonstration built on the Thoresby experience. It demonstrated the system's ability to tap the excess heat of combustion to boil water over a 12-month period through an internal heat recovery subsystem. In addition, it proved that the system would provide reliable performance even under variations in VAM flow typical at active underground coal mines. This award-winning project[6] illustrated the potential for TFRRs to be used for a variety of energy applications, such as water or space heating, drying, and electricity generation. Subsequently, VAM-based electrical power generation was demonstrated on a commercial scale at the West Cliff Colliery in New South Wales. Dubbed WestVAMP (West Cliff Ventilation Air Methane Project), the project started operation in April 2007, consuming 250,000 m^3/h (150,000 scfm) of ventilation air (0.9 percent methane[7]) to generate 6 MW of electrical power (see Figure 3). Combining VOCSIDIZER™ units with a conventional steam turbine running on superheated stream, the system produces electrical power which is fed to the West Cliff colliery.

[4] Some contaminants may bond with or react with the catalyst, thereby reducing its ability to chemically affect the reaction that it is intended to catalyze.

[5] http://www.megtec.com/energy_from_coal_mine_ventilation_air_methane-p-682.html

[6] The Appin demonstration project was named Best Greenhouse Gas Project in April of 2005 by the Australian Coal Association Research Programme.

[7] This concentration is maintained by combining drainage gas with the mine's ventilation exhaust flow.

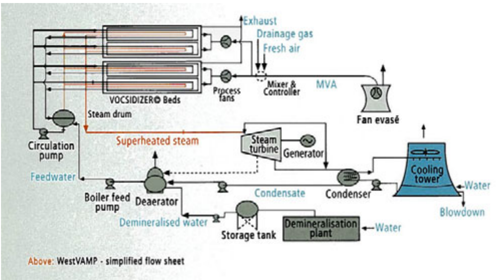

Figure 3. WestVAMP Schematic

WestVAMP is an ongoing project which has won its own awards.[8] As of December 2007, the project has operated without interruption for two months. As a result, interest in deployment of this technology is growing.

The technical efficacy of TFRRs to reliably and safely oxidize the very low concentrations of methane contained in coal mine ventilation exhausts has now been proven, as has its ability to serve as an energy plant, supporting thermal applications and electrical power generation.

4 Technology Deployment Challenges

In light of the field tests demonstrating their technical reliability, deployment of flow reversal oxidizers at active underground coal mines worldwide is desirable for a number of compelling reasons:

- Making productive use of an otherwise wasted source of clean energy
- Producing revenues through the sale of equipment
- Producing revenues through the sale of electricity or thermal energy
- Reducing greenhouse gas emissions

There remain two potential hurdles to widespread deployment. One relates to market economics, the other to regulatory approval.

A VAM-oxidation project at a given coal mine will have to be economically attractive as well as technically feasible. For investors to commit financial resources to a project, it needs to offer an attractive return on investment (ROI) compared with other available opportunities. ROI is dictated by market conditions, such as the price of electricity or other project outputs (e.g., space heat). In addition, the ROI is a function of the methane content of the oxidizer inflow. For example, in power generation applications, the more methane that is oxidized per unit of time, the more electricity produced. Currently available oxidizers appear to offer the best ROI for power generation when inflow VAM concentrations are in the 0.9-1.0 percent range. This concentration range allows projects to generate considerable electricity while avoiding excessive heat of oxidation, which may compromise the physical integrity of the oxidizer. Some projects will need to secure a supply of drainage gas that can be added to the mine exhaust flow to increase its methane concentration and maximize power output and ROI. In addition, it is possible that VAM-based power may be eligible to receive a premium power sale price based on its environmental benefits. This might be achievable in cases where a green power market can be accessed or where utilities are required to meet renewable energy portfolio standards (such as in the Commonwealth of Pennsylvania).

Similarly, supplemental revenues from the sale of carbon emission reductions may be required to bring projects with otherwise marginal economics to a point where investors find them attractive. Again, the more methane that is oxidized per unit of time, the greater the carbon emission revenue stream and its contribution to project ROI. MEGTEC estimates (Mattus, 2007) that with a carbon sale price of US$10.00/tonne CO_2e, VAM oxidation projects begin to offer attractive payback times (e.g., 3 to 6 years) when VAM concentrations are greater than 0.6 percent.

In addition to successfully addressing market constraints, VAM-oxidation projects will need to secure the approval of mine safety regulators. In the United States, deployment of VAM oxidizers at active underground coal mines requires approval of the Mine Safety and Health Administration (MSHA). Although TFRRs are deployed at facilities worldwide and WestVAMP has been approved by Australian regulators, oxidizers have not been through the approval process (with MSHA) for use at a U.S. coal mine.

5 The Windsor Mine VAM Demonstration Project

5.1 Purpose

The U.S. Department of Energy and the USEPA are funding the first U.S. field demonstration of VAM oxidation at the abandoned Windsor Mine in West Liberty (in the northern panhandle of West Virginia). MEGTEC is providing technology and support to the project. CONSOL Energy is operating the demonstration and selected the Windsor Mine as the host site once it was determined that the mine could produce a sufficient supply of drained methane at concentrations adequate to support auto-oxidation. Since it is an abandoned mine, the Windsor site has no workers underground and thus can serve as an ideal site to test the operational reliability and safety of the technology. Since there is no ventilation fan in place, drained methane is mixed with air to obtain a methane-in-air blend that is typical of VAM (i.e., simulated VAM).

The Windsor project (see Figure 4) is intended to provide hands-on domestic experience in operating a VAM oxidizer and to confirm that a VAM project will not affect operations at an active U.S. mine. The demonstration is intended to verify (1) VAM destruction efficiency, (2)

[8] Highly commended in the NSW Minerals Council's 2007 Excellence Awards, and recipient of the Excellence in Energy Award from the Australian Institute of Energy.

system operation safety, and (3) reliable operation of the system under field conditions.


Figure 4: Windsor Mine VAM Demonstration Project

The system ran at full load for the first time on February 11, 2007. System commissioning was completed in April, and unmanned operation began on May 9, 2007.

Commissioning included testing various components of the system to ensure their proper operation, including:

- Verifying mass flow measurements, setting pressure switches, and checking bed thermocouple readings.
- Testing fail-safe shutdown systems (some during operation and others simulated electronically):
  - Inlet methane analyzer to trip at the set point of 1.2 percent methane concentration
  - High flow in the mine methane line
  - High and low flow in the duct

Also during commissioning, an experimental test plan was implemented that tested the operating limits of the equipment under the following six throughput conditions:

- 0.9% CH_4 @ 15,000 scfm
- 0.3% CH_4 @ 15,000 scfm
- 0.9% CH_4 @ 30,000 scfm (maximum flow)
- 0.3% CH_4 @ 30,000 scfm (maximum flow)
- 0.6% CH_4 @ 22,500 scfm

During testing, gas samples were taken of the abandoned mine gas, oxidizer inlet, and oxidizer stack to measure the methane concentration. The latter two data sets (i.e., CH_4 concentrations in and out) define the system's destruction and removal efficiency (DRE). The DRE is less than 100 percent in a flow-reversal system because some methane (approximately 3 percent of the flow) blows out of the system without being oxidized as the poppet valves actuate. Thus, the overall system DRE is on the order of 97 percent.

Temperature at the exhaust stack follows a "zigzag" profile due to the flow reversal regime. The outlet temperature repeatedly swings from approximately 300°F to 500°F and back again as the system cycles every 2 minutes, although the middle bed temperature is maintained at a steady temperature of about 2,000 °F.

The single-unit VOCSIDIZER™ system is designed with a plenum[9] on the top and another on the bottom, so the direction of air flow changes from top to bottom and then from bottom to top, repeatedly. The overall system includes an air compressor which powers certain instruments, primarily the poppet valves that control the direction of airflow.

5.2 Unattended Operation and Testing

During the ~8 month demonstration period, the unit has run continuously at a 0.6% CH_4 concentration and an airflow feed rate of 30,000 scfm. The operating plan includes continuous data capture occurring from 1 second to 5 minute intervals. System sensors are designed to trigger shutdowns if any of the following upsets occur:

- Power to the system is interrupted
- The programmable logic controller back-up battery is defective
- Dampers operate improperly
- Bed temperatures are out of range (high or low)
- Inlet methane concentration set point is exceeded
- Pressures are out of range (high or low)
- Thermocouples are defective
- Poppet valves leak

Some of these upsets did in fact occur, and the system safety controls responded appropriately. For example, power was interrupted on a number of occasions due to local electricity outages caused by severe storm events.

Key data captured throughout the test period are:

- Mine gas flow
- Simulated ventilation air methane concentration
- Simulated ventilation air inflow volume
- Oxidizer bed temperatures
- Pressure drop across the bed

The operating plan also includes a set of three one-hour emissions tests conducted at intervals during the demonstration period to verify that the oxidizer meets applicable air emission regulations. The tests measured the following emissions: SOx, NOx, CO, CO_2, O_2, VOCs, and particulate matter. It was determined that the unit does operate in compliance with air pollution standards.

5.3 Demonstration Results

During the demonstration, certain operational issues were encountered which, in comparison with oxidizer experience at industrial settings, appear to be unique to coal mine operations that do not include heat extraction. These include:

[9] An open chamber from which the ventilation air is distributed through the bed.

- Location: The remoteness of the site and the fact that it is unattended meant that response to minor upsets required a longer-than-normal time frame. At active coal mines where operational and maintenance personnel are always on site, system restarts can be made more quickly once the cause of shut down is resolved.
- VAM simulation: To ensure safe operation of the oxidizer, a methane sensor with both high accuracy and a rapid response time is required. The sensor was not able to meet both performance goals and adjustments continue to be made.
- Extreme temperature fluctuations: The large temperature swings in the air plenum require special design considerations.

An alternative methane sensor was tried, as were alternative locations for the sensor in the gas/air stream. Problems can be expected in any test and CONSOL and MEGTEC have worked diligently to resolve these issues.

As of November 2007, the demonstration project had run for a total of 1,301 hours unmanned. To date the demonstration project has shown that the TFFR is effective in oxidizing simulated VAM containing less than 1.0 percent methane (without heat recovery) and has proven that the safety subsystems in the oxidizer design perform as intended. Whenever a safety-related fault was evidenced, automatic shutdown of the system occurred as planned. In addition, the experience gained in this demonstration provides substantial insight into how the oxidizer operates with VAM and how it can be deployed under field conditions. If this U.S. demonstration accelerates application of VAM oxidation technology, it will make a significant contribution to addressing global climate change. Although this demonstration is only oxidizing simulated VAM and not capturing its energy content, ultimately VAM mitigation projects can provide the opportunity to put the energy to beneficial use. Such use would further increase the benefits of deploying this technology by offsetting coal with a clean energy source.

6 Summary and Conclusion

The ability of flow reversal oxidizers to operate successfully on VAM has been demonstrated at coal mines in the United Kingdom and in Australia. The world's first commercial scale VAM-to-power project has been in operation in Australia since April 2007. Although no commercial installation has been implemented in the U.S., CONSOL Energy has operated a demonstration project using the MEGTEC's VOCSIDIZER™ technology at its abandoned Windsor Mine in West Virginia. The project encountered some operational problems, but has achieved considerable operating time and provided tangible evidence of the technology's ability to oxidize VAM safely.

Key results from the demonstration are that safety subsystems operate as intended. This is an important outcome, since mine safety regulators will need clear assurance that deploying these systems at active mines in the U.S. will pose no additional risk to miners, especially those underground. In addition, the demonstration has provided valuable insight into how this technology operates and what issues will need to be addressed in future field deployment settings.

The USEPA estimated that, globally, upper bound estimates for the VAM mitigation market in 2002 were 167.1 million tonnes CO_2e (11.7 Bm^3 methane), producing \$8.4 billion in equipment sales and \$880 million in annual electricity revenues. Almost half of the VAM emission market potential estimated by USEPA was accounted for by China alone. Combining the market potential for the United States and Australia, where the most focused VAM technology demonstration activity has been carried out in recent years, these three countries account for over 65 percent of total global potential. Since the USEPA study, global carbon market prices have increased to about three times the value used in that assessment. Thus, global implementation of VAM oxidation technology offers substantial potential environmental and economic benefits.

Acknowledgments

The authors gratefully acknowledge the assistance of Deborah Kosmack (Research Engineer, CONSOL Energy Research & Development) and Richard Winschel (Director, Coal Utilization, CONSOL Energy Research & Development) in providing key information relating to the Windsor demonstration project and in reviewing this paper.

References

Hamilton et al., 2007. *State of the Voluntary Carbon Markets 2007: Picking Up Steam,* Hamilton, K, Bayon, R, Turner, G, and Higgins, *D,* New Carbon Finance and The Ecosystem Marketplace, July.

Mattus, R, 2007. *In Full Operation – The World's First VAM Power Plant*, presented at the Methane to Markets Partnership Expo, Beijing, China, October 30 – November 1, 2007.

USEPA, 2003. *http://www.epa.gov/coalbed/pdf/ventilation _air_ methane.pdf.* Assessment of the Worldwide Market Potential for Oxidizing Coal Mine Ventilation Air Methane, U.S. Environmental Protection Agency, EPA 430-R-03-002, July.