Mitigation of Methane Emissions from Coal Mine Ventilation Air: An Update

F. Peter Carothers
Senior Engineer, Methane Mitigation, International Resources Group, Washington, DC USA
H. Lee Schultz
Director, Environmental Programs, International Resources Group, Washington, DC USA
Clark C. Talkington
Manager, Coalbed Methane Outreach Program, US Environmental Protection Agency, Washington, DC USA

ABSTRACT: Control of methane emissions from mine ventilation systems has been a challenging goal because of the magnitude of typical airflows coupled with very low methane concentrations. The authors evaluated the technical and economic feasibility of several emerging systems that may accept up to 100 percent of the flow from a gassy underground coal mine ventilation shaft, oxidize the entrained methane, and produce marketable energy. This paper discusses flow-reversal oxidizers that provide heat for producing thermal or electric energy, lean-fueled combustion turbines, and a hybrid waste coal and methane power plant. The paper also covers research into methane concentration techniques and the use of ventilation air methane as combustion air for a variety of prime movers. When ventilation shafts emit methane concentrations approaching 1.0 percent, energy prices are high, and revenues from greenhouse gas emission reduction offsets are available, it will be possible to operate a profitable energy plant fueled with ventilation air methane.

1 INTRODUCTION

The Coalbed Methane Outreach Program (CMOP) is a part of the US Environmental Protection Agency's (USEPA) Climate Protection Partnerships Division. CMOP is a voluntary program that works with coal companies and related industries to identify technologies, markets, and means of financing the profitable recovery and use of coal mine methane (CMM), a powerful greenhouse gas (GHG), that would otherwise be vented to the atmosphere. With a global warming potential that is 21 times that of carbon dioxide[1], methane capture and use offers a particularly attractive opportunity to achieve substantial GHG emission mitigation.

CMOP assists the coal industry by profiling CMM project opportunities, conducting mine-specific technical and economic assessments, and identifying private, state, local, and federal institutions and programs that could catalyze project development. In past years CMOP has been instrumental in helping coal mines in the US and abroad to successfully implement CMM drainage and use projects, thereby markedly reducing the volumes of methane that currently enter the atmosphere. Although there remain opportunities to recover drained gas, CMOP recognizes that to achieve continued reductions in methane emissions from coal mines over the long term, it is necessary to target ventilation system emissions. Ventilation air exhaust streams at gassy underground coal mines are characterized by very large airflows, typically ranging from 47 to 470 cubic meters per second (100,000 to 1,000,000 cubic feet per minute), containing very low concentrations of methane (ranging from 0.1 to over 1.0 percent). Most VAM occurs in concentrations that are between 0.3 to 0.5 percent.

Four years ago at the 8th US Mine Ventilation Symposium, Peter Carothers of International Resources Group presented an initial overview of the then developing technologies for ventilation air oxidation (Carothers and Deo, 2000a). After four years USEPA has witnessed encouraging progress in the pursuit of feasible and economically viable technologies that can oxidize and use the energy content of VAM. Additionally, a number of new technologies have emerged. This paper provides an update on the technological innovations occurring and presents new information on markets for ventilation air methane (VAM).

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[1] Note that the Intergovernmental Panel on Climate Change, in its Third Assessment report *Climate Change 2001*, increased the global warming potential value for methane from 21 to 23. However, the 21 value is still used as the standard for calculating carbon dioxide equivalents in emission inventories, carbon emission reduction transactions, etc.

2 TECHNOLOGY OVERVIEW

USEPA has identified several types of downstream technologies for destroying or beneficially using the methane contained in ventilation air in a USEPA report published in 2000 (Carothers and Deo, 2000b). These technologies fall into the following general categories:

- Flow-reversal oxidizers
- Lean-burn combustion turbines
- Coal and VAM hybrid system
- Methane concentration
- Use as an ancillary fuel

Each of these technology categories is described below.

2.1 *Flow-reversal oxidation*

Oxidizers use a type of recuperation that retains the heat of oxidized methane in a ceramic bed, which in turn ignites new incoming VAM. USEPA has identified two basic oxidizer types, the thermal flow-reversal reactor (TFRR) and the catalytic flow-reversal reactor (CFRR). MEGTEC Systems (De Pere, Wisconsin), has developed a TFRR known as the VOCSIDIZER® that has been adapted to oxidize VAM. Canadian Mineral and Energy Technologies (CANMET – a national laboratory in Varennes, Quebec, Canada) has developed a CFRR expressly for mine ventilation air. Both technologies employ similar principles to oxidize methane contained in mine ventilation airflows. Based on laboratory and field experience, both units can sustain operation (i.e., can maintain oxidation) with ventilation air having uniform methane concentrations down to approximately 0.1 percent. For practical field applications where methane concentrations are likely to vary over time, however, a practical average lower concentration limit at which oxidizers will function reliably is considered to be 0.15 percent.

2.1.1 *Thermal flow-reversal reactor*

Figure 1 shows a schematic of the Thermal Flow-Reversal Reactor (TFRR). The equipment consists of a bed of silica gravel or ceramic heat-exchange medium with a set of electric heating elements in the center. To start oxidation, electric heating elements preheat the middle of the bed to or above the temperature required to initiate autoignition, i.e., ≥1000°C (1832°F). Ventilation air containing methane enters at ambient temperature and flows through the reactor in one direction, and its temperature increases until oxidation of the methane takes place near the center of the bed.

The hot products of oxidation continue through the bed, losing (transferring) heat to the far side of the bed in the process. When the far side of the bed is sufficiently hot and the near side has cooled due to the inflow of ambient-temperature ventilation air, the reactor automatically reverses the direction of ventilation airflow. The ventilation air now enters the far (hot) side of the bed, where it encounters autoignition temperatures near the center of the bed and then oxidizes. The hot gases again transfer heat to the near (cold) side of the bed and exit the reactor at a temperature just modestly above ambient. Then, the process again reverses.

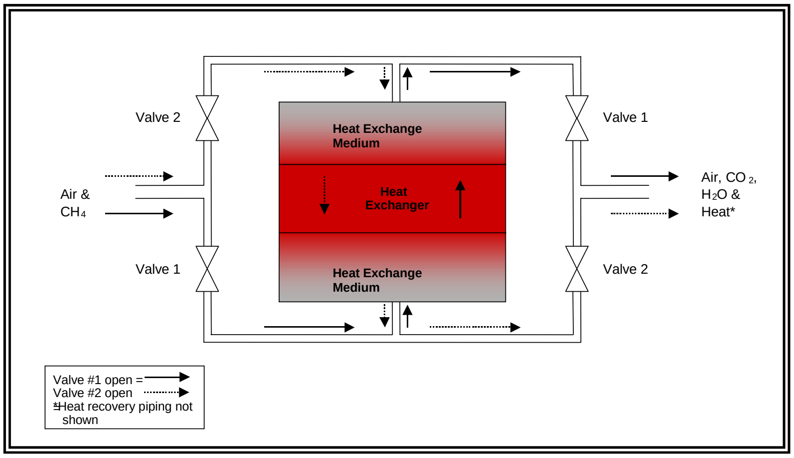

Figure 1. Thermal Flow-Reversal Reactor

TFRR units are effectively employed worldwide to oxidize industrial volatile organic compound (VOC) streams. Furthermore, the ability of MEGTEC’s VOCSIDIZER® to oxidize VAM has been demonstrated in the field (Kallstrand and Zak, 2000-2003).

2.1.2 *Catalytic flow-reversal reactor*

Catalytic flow-reversal reactors adapt the thermal flow reversal technology described above by including a catalyst to reduce the autoignition temperature of methane by several hundred degrees Celsius, i.e., to as low as 350°C (662°F). CANMET has demonstrated this system in pilot plants and is now in the process of awarding a license to

Lefebvre Freres Ltd., of Montreal, Quebec, Canada, to commercialize the design (Sapoundjiev et al., 2000-2003).

2.1.3 *Energy conversion from a flow-reversal reactor*

There are several methods of converting the heat of oxidation from a flow-reversal reactor to electric power, which is the most marketable form of energy in most locations. The two methods being studied by MEGTEC and CANMET are:

- *Use water as a working fluid.* Water is pressurized and forced through an air-to-water heat exchanger in a section of the reactor that will provide a non-destructive temperature environment, e.g., below 800°C (1472°F). The hot pressurized water is flashed to steam and the steam is used to drive a steam turbine-generator. One vendor intends to superheat the steam in a separate heat exchanger. If a market for low-quality steam or hot water is available the facility can send exhausted steam to that market. If none is available, the steam can be condensed and the water returned to the pump to repeat the process.
- *Use air as a working fluid.* Ventilation air or ambient air is pressurized in a gas turbine's compressor and sent through an air-to-air heat exchanger that is embedded in a section of the reactor that stays near 800°C (1472°F). The heated compressed air, serving as the gas turbine's working fluid, passes through the expansion section of the turbine, which powers the generator. If drained CMM such as gob gas is available, it may be used in an external combustor to raise the temperature of the working fluid to more nearly match the design temperature of the turbine inlet. The turbine exhaust may be used for cogeneration (see Figure 2), if thermal markets are available, or for heating incoming air.

Since affordable heat exchanger temperature limits are below those used in modern prime movers, efficiencies for both of the energy conversion strategies listed above will be constrained by such limits and fairly modest. The overall plant energy conversion efficiencies (with a supplemented VAM concentration of 1.0 percent) assumed for the cost estimates discussed later in this paper are expected to be in the neighborhood of 17 percent after accounting for power allocated to drive the fans that force ventilation air through the reactor.

2.2 *Lean-burn combustion turbines*

A number of engineering teams are striving to modify selected combustion (gas) turbine models to operate directly on VAM or on VAM that has been enhanced with more concentrated methane such as drained CMM. USEPA continually reviews the progress of research, development, and demonstration phases for several systems when and as their sponsors release information. Four of these systems are briefly described below. Two systems are based on full-sized commercial turbines, and two are modifications of "microturbines" that are currently sized in the range of 30 to 250 kW per unit.

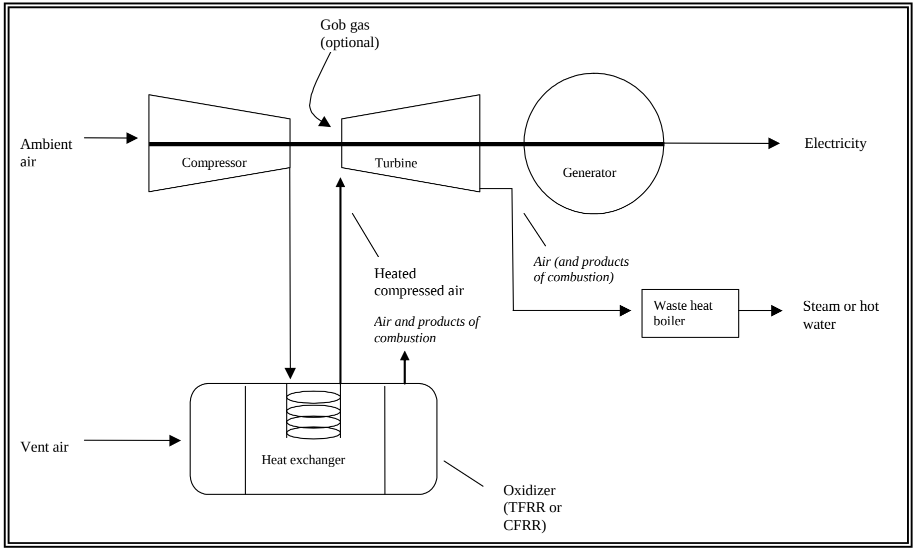

Figure 2. Schematic of Cogeneration Option using Air as a Working Fluid

2.2.1 *Carbureted gas turbine*

A carbureted gas turbine (CGT) is a gas turbine that employs a patented external combustor where the reaction is at a lower temperature, 1200°C (2192°F), than for a normal turbine, thus eliminating any NOx emissions. The system's fuel, a homogeneous mixture of VAM and supplemental methane, enters via the air inlet to an aspirated turbine. It is then compressed and heated in an exhaust gas recuperator to 450°C (842°F).

The CGT requires a methane/air mixture of 1.6 percent by volume, so most VAM sources, which typically contain only about 0.4 percent methane, would require enrichment. In fact, significant amounts of supplemental fuel would be required to raise the methane concentration to the 1.6 percent level.

Energy Developments Limited (EDL) of Australia is testing the CGT (see Figure 3) on ventilation air at the Appin coal mine in New South Wales, Australia. EDL is using a modified solar gas turbine model 3000R (rated at 2.7 MW) for this demonstration (Chapman, 2001-2003).

Figure 3. EDL Carbureted Gas Turbine Installation

2.2.2 *Lean-fueled turbine with catalytic combustor*

CSIRO Exploration & Mining of Australia, a government research organization, is developing a catalytic combustion gas turbine (CCGT) that can beneficially use methane in coal mine ventilation air (Su, 2001-2003). The CCGT technology being developed oxidizes VAM in conjunction with a catalyst. The turbine draws a very lean fuel/air mixture into the air intake, compresses it, and combusts it in a catalytic combustor. CSIRO's non-conventional turbine will not use combustion air for internal cooling, thus allowing the air intake to contain fuel. CSIRO hopes to operate the system on a 1.0 percent methane mixture to minimize supplemental fuel requirements. The catalyst allows the methane to ignite at a lower, more-easily achieved temperature. CSIRO continues with its research and plans for full commercialization of the VAM CCGT.

2.2.3 *Lean-fueled catalytic microturbine*

Two US companies, FlexEnergy and Capstone Turbine Corporation, are jointly developing a line of microturbines (starting at 30 kW) that will operate on a methane-in-air mixture of 1.3 percent. FlexEnergy, using funding from US Department of Energy/National Renewable Energy Laboratory and the California Energy Commission, has successfully tested a 30 kW prototype unit in 2003 on a simulated VAM with a concentration at 1.4 percent, just above the targeted 1.3 percent. Each unit's components fit inside a compact container that requires no field assembly. The single moving part, rotating on an air bearing, is a shaft on which is mounted the compressor and the turbine expander. Other components include: a recuperator that preheats the VAM mixture, a catalytic combustion chamber allowing low-temperature ignition, a generator, and a generator cooling section. To better serve the VAM market, FlexEnergy is investigating designs that will reduce the required VAM concentration to below 1.0 percent because large amounts of supplemental fuel would be required to raise the methane concentration to 1.3 percent. The company is also working to increase unit sizes to over 200 kW so that fewer units will be needed at each installation (Prabhu, 2001-2003).

2.2.4 *Lean-fueled recuperated microturbine*

Ingersoll-Rand (IR), a large US company, has developed a lean-fueled version of its PowerWorks Microturbine. The current prototype is rated at 70 kW, and a 250 kW version is under design. VAM is drawn into the PowerWorks microturbine and compressed. It then passes through a patented recuperator that captures heat from escaping exhaust gasses and preheats the incoming VAM. This step significantly boosts the unit's overall efficiency. The preheated, compressed VAM then enters the combustion chamber where it is ignited, producing hot, rapidly expanding gasses. These gasses flow through the turbine's first expansion section, which drives the compressor, and then through a second turbine called the "free power" turbine. Exiting gasses then pass through the hot side of the recuperator and exit the unit. IR has successfully tested its lean-fuel microturbine on a 1.0 methane concentration and the company reports that they can run on 0.86 percent methane. IR plans a field test of the 70 kW prototype as soon as they can find a mine willing to offer a test site. The 250 kW version will be ready in early 2005. The next step will be to greatly increase unit size to well over 1 MW, and that would require the cooperation of a manufacturer of conventional gas turbines to allow IR to replace the combustion section with its own design (Reinks, 2002-2003). The IR design offers the advantage of being able to operate with a smaller amount of supplemental fuel.

2.3 *Hybrid coal- and VAM-fueled gas turbine*

CSIRO and Liquatech are developing an innovative system in Australia to oxidize and generate electricity with VAM in combination with waste coal. CSIRO has constructed a 1.2 MW pilot plant that cofires waste coal and VAM in a rotary kiln, captures the heat in a high-temperature air-to-air heat exchanger, and uses the clean, hot air to power a gas turbine (see Figure 4), (Wendt et al., 2001).

Depending on site needs and economic conditions, VAM can provide from about 15 to over 80 percent (assuming a VAM mixture of 1.0 percent) of the system's fuel needs, while waste coal provides the remainder. Waste coal and ventilation air enter the rotating kiln in the same direction. The coal's heat of combustion ignites the VAM, and a large percentage of that heat is transferred to an air-to-air heat exchanger that operates at about 900^{o}C (1652^{o}F). Ambient air, pressurized by the gas turbine's (Allison C-18) compressor, flows through the heat exchanger's secondary loop, heats to 900^{o}C (1652^{o}F), and expands through the turbine's power section. Part of the compressor's output is directed to the turbine cooling path. This system is especially well suited for mines, such as those in Australia, that generate a significant percentage of high-ash content waste coal and that can market the lightweight, expanded aggregate that results from the process.

Figure 4. CSIRO-Liquatech 1.2 MW Hybrid Coal and Gas Turbine

2.4 *Concentrators*

VOC concentrators offer another possible option for application to VAM. During the past 10 years the use of such units to raise the concentration of VOCs in industrial-process air exhaust streams that are sent to VOC oxidizers has increased. Smaller oxidizer units are now used to treat these exhaust streams which in turn has reduced capital and operating costs for the oxidizer systems. Ventilation air typically contains about 0.4 percent methane by volume. Conceivably, a concentrator might be capable of increasing the methane concentration in ventilation airflows to about 20 percent. The highly reduced gas volume with a higher concentration of methane might serve beneficially as a fuel in a gas turbine, reciprocating engine, etc. Concentrators also might prove effective in raising the methane concentration of very dilute VAM flows to levels that will support economically viable oxidation or lean-fuel gas turbine projects.

Of the various styles of concentrators employed in industrial applications, fluid bed concentrators are expected to offer the greatest chance for VAM concentration. The fluid bed concentrator consists of a series of perforated plates or trays supporting an adsorbent medium (e.g., activated carbon beads). The process exhaust stream enters from the bottom, passing upward through the adsorption trays, fluidizing the adsorbent medium to enhance capture of organic compounds. The adsorbent medium, which is now heavier because of the adsorbed organic material, falls to the bottom of the adsorber section and is fed to the desorber. The desorber increases the temperature of the medium, causing it to release the concentrated organic material into a low-volume, inert gas stream. In this continuous operation, the regenerated medium is fed back to the adsorber vessel for reuse.

Environmental C & C, Inc. (Clifton Park, New York) manufactures a fluid bed concentrator. With USEPA assistance, Environmental C & C tested that system's efficacy on simulated VAM using a series of methane-in-air mixtures. While technically successful, the tests indicated that a more efficient, faster reacting adsorbent medium will be needed to permit VAM concentration to be an economically viable system component. The company will continue to search for an adsorbent that can offer an affordable concentration element to VAM mitigation plants (Cowles, 2002).

2.5 *VAM used as an ancillary fuel*

While the primary focus of this paper is on strategies that can oxidize major fractions of global VAM emissions, a brief mention of technologies that use VAM only as an ancillary or supplemental fuel is in order. Such technologies rely on a primary fuel other than VAM and are able to accept VAM as all or part of their combustion air to replace a small fraction of the primary fuel. The largest example of ancillary VAM use occurred at the Appin Colliery in Australia, where 54 one-megawatt Caterpillar engines used mine ventilation air containing VAM as combustion air. Although the VAM portion of the project currently is inactive, the success of the project in the field proved IC engine's capability in handling the VAM stream for this specific use.

Figure 5. Appin Project, New South Wales, Australia

Similarly, the Australian utility, Powercoal, plans to install a system that uses VAM as combustion air for a large coal-fired steam power plant. In addition, the US Department of Energy funded a research project to use VAM in concentrations up to 0.5 percent as combustion air in a gas turbine manufactured by Solar. Even the CSIRO hybrid coal and VAM project described above falls in the category of ancillary VAM use when waste coal combustion is maximized and VAM use is limited to stoichiometric levels of combustion air.

3 TECHNOLOGY SUMMARY

The table below summarizes the descriptions and status of development of the systems that USEPA is tracking.

Table 1. Technology used by USEPA.

Vendor / System	**Description**	**Country**	**Development Status**
MEGTEC / VOCSIDIZER®	Thermal flow-reversal reactor (oxidizer)	US and Sweden	Completed small field trial; produced steam
CANMET - Lefebvre Freres Ltd. / CH4MIN	Catalytic flow-reversal reactor (oxidizer)	Canada	Completed laboratory trials; no heat recovery
EDL / Carbureted gas turbine (CGT); Isentropic Systems Ltd	Lean-fueled (1.6%) Solar gas turbine with patented combustor	Australia	Undergoing full-scale trials with simulated VAM; results delayed
CSIRO / Lean-fueled turbine with catalytic combustor	Lean-fueled (1.0%) gas turbine with catalytic combustor	Australia	Research phase scheduled to be complete in 1 to 2 years
FlexEnergy / Lean-fueled catalytic microturbine	Lean-fueled Capstone microturbine (1.3%)	US	Field-tested a 30 kW unit on simulated VAM
Ingersoll-Rand / Lean-fueled recuperated microturbine	Lean-fueled (1.0%) IR Power Works microturbine	US	Factory-tested a 70 kW unit on simulated VAM
CSIRO / Hybrid coal and VAM fueled gas turbine	Waste coal and VAM cofired in rotary kiln; compressed air heated in heat exchanger powers a gas turbine	Australia	Factory-tested a 1.2 MW unit on waste coal and simulated VAM
Environmental C&C / VOC concentrator	Fluid bed adsorbent concentrator	US	Bench-scale tests did not produce satisfactory results
EDL / Ancillary VAM use	VAM used as combustion air in Caterpillar 1 MW engines	Australia	Successfully operated at commercial scale

4 ENERGY MARKETS

Each of the technologies described above (with the exception of concentration and ancillary use) produces a heated working fluid that rotates a turbine that turns an electric generator. It is feasible for the oxidizers to simply generate a form of thermal energy to serve markets near the host mine. It may also be possible for the gas turbine systems to remove the power turbine and end up with only a compressed heated gas that could serve a thermal energy market.

Thermal markets might include mine ventilation air heating, coal drying, space heating, process heating, etc. USEPA, however, has decided to concentrate on projects that deliver electric power to either the mine's electric demand or to the grid (Schultz et al, 2003). There are several practical reasons for this:

- Electric power markets are everywhere, while suitable thermal markets are often remote from the host mine.
- Thermal markets are often seasonal, single shift, or otherwise non-continuous.
- Electric power usually carries a higher price per unit of energy.
- Electric power markets receive power continuously, and that is very important because a VAM facility must receive fuel continuously; the plant will be designated as "must run".

If a high-value, continuous thermal market were located near to the ventilation shaft, however, the developer should certainly evaluate serving such a market. But electric power will usually be the energy commodity of choice.

The production of electric power has the further advantage of being able to produce a constant supply of lower grade, but often useful, thermal energy by the use of cogeneration. For example, each of the gas turbines described above produce a waste heat that is in the temperature range of many needs.

Another market that may be available is the market for of carbon emission reductions (see discussion below). By merely oxidizing VAM in a thermal oxidizer that has no embedded heat exchanger the project will produce emission reductions that may be sold to buyers who need offsets.

5 CARBON EMISSION REDUCTION OFFSETS

As mentioned earlier, methane has a global warming potential 21 times that of carbon dioxide. Thus, methane emission mitigation offers the possibility of generating substantial streams of carbon emission reductions (in terms of carbon dioxide equivalent, or CO_2e). Those emission reductions in turn can offer substantial monetary value through the public and private markets that exist in the U.S. and around the world. Generally, project developers realize the economic benefits either by trading the actual emission reductions through a commodity trading program, receiving tax credits or similar incentives, or receiving equity funds to invest in recovery projects in exchange for the title to the emission reductions.

According to a report from the World Bank's Prototype Carbon Fund (Lecocq and Capoor, 2002), trading in greenhouse gas emissions in 2002 more than doubled over that in 2001, rising from 29 million tonnes CO_2 equivalent to 71 million tonnes. The prices paid range from US$4.00-$6.00 per tonne. In the U.S. prices in the private markets have tended to be much lower.

Although reported individual emissions transactions have ranged from <10,000 to >10,000,000 tonnes, typical project-based volumes are in the 1,000,000 tonne range with unit prices varying considerably depending on a number of factors. Unit sale prices have been reported to range from roughly US$1.50 to as high as US$18.00 per tonne CO_2e. Thus, even at the lower end of the unit price range, the internal rate of return of projects mitigating substantial quantities of methane can be significantly enhanced through the sale of the carbon credits that they generate.

6 COST ANALYSIS

Some of the vendors listed above have supplied USEPA with preliminary estimates of performance and cost (both capital and operating) of their systems. The authors anticipate that more information will be available as soon as field demonstrations at commercial scale have been completed for each system. As expected, the costs for installations that oxidize VAM, recover heat, and generate electricity are higher than for conventional systems because of the very nature of VAM – dilute and moving in huge volumes. USEPA compiled available early projections of performance and costs and found the following:

- Projected cost estimates for the TFRR, CFRR, and one lean-fueled turbine fell in a reasonably narrow range.
- Lean-fuel turbines exhibit better efficiency in converting VAM to electric power.

- Thus, for a power facility of comparable size lean-fuel turbines will oxidize less VAM and earn fewer carbon credits than oxidizer systems.
- The parameter that most significantly affected performance and, consequently, project profitability, is VAM concentration; the higher the better, up to about 1.0 percent.
- Several mine sites that exhibit favorable physical and economic conditions would produce attractive power projects that yield a before-tax internal rate of return of 25% or better.
- Many installations with blended VAM concentrations at or near 1.0% could be economically viable where the project receives about $0.05 per kWh, or receives some favorable combination of electric revenue and carbon credit payments.

Using cost assumptions that combine two oxidizer system estimates, USEPA constructed a simple cost model for a project that can supply VAM supplemented, if necessary, to reach a consistent concentration of 1.0%. The model contains conservative economic and financial assumptions, and it assumes that the project owner would require a 25% before-tax IRR. With no carbon credit payments the project would have to sell its power for about $0.05 per kWh, but with a carbon credit sale price of about $2.28 per tonne of CO_2e the project could achieve its target IRR with a power price of only $0.035 per kWh. Naturally these results would change with significant variations of the many parameters upon which the project depends, but the example shows that even with current power and carbon emission reduction pricing many VAM projects can be economically viable.

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